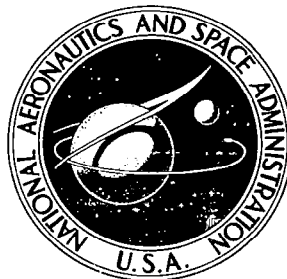


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LIQUID METAL BOILING INCEPTION

*by C. M. Sabin, H. F. Poppendiek, G. Mouritzen,
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16. Abstract An experimental study of the inception of boiling in potassium in forced convection is reported. The boiler consisted of a 0.19-inch inside diameter, niobium-1% zirconium boiler tube approximately six feet long. Heating was accomplished by direct electrical tube wall conduction. Experiments were performed with both all-liquid fill and two-phase fill startup sequences and with a range of flow rates, saturation temperatures, inert gas levels, and fill liquid temperatures. Superheat of the liquid above the equilibrium saturation temperature was observed in all the experiments. Incipient boiling liquid superheat ranged from a few degrees to several hundred. Comparisons of these data with other data and with several analytical treatments are presented.					
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I. INTRODUCTION

Potassium liquid has, in common with many other liquids, the ability to superheat under some circumstances far above the liquid-vapor saturation line defined by thermodynamic equilibrium. The mechanisms and controlling variables which affect liquid superheating are not completely understood, but some of the parameters appear to include surface roughness, number and size of cavities in the boiler surface, flow velocity, and inert gas level in the system.

Geoscience's studies were in support of the Potassium Rankine space power system which used a lithium-heated, potassium boiler and was described in NASA TM X-1919. There was evidence that gross liquid superheat could exist in such systems and when released it might cause damage to the turbine. The power plant would likely be started in the two-phase mode at moderate temperature levels (i.e., $< 1800^{\circ}\text{F}$). Therefore, the experimental work was done under these conditions. The purpose of this study was to explore the problem of boiler startup. An in-depth research effort was not intended. The program, which was approximately a three-man-year effort, consisted of three tasks. The first of these was the preparation of the experimental apparatus, including design of the test boiler and its insert, development of procedures for controlling or measuring the principal variables believed to be important, and the physical modification of the hardware. The second task consisted of the actual experimental work and the last one involved analysis and the correlation of existing liquid metal data in support of the experimental program.

There are two apparently different liquid superheats which have been described in the literature. These have been called incipient superheat and nucleating superheat. Incipient superheat is that value encountered in a liquid metal when no boiling is taking place in the region, while nucleating superheat is that

quantity required to sustain steady boiling. Both of these temperature increments were measured in the experimental program.

There are two distinct methods which can be used to start up a liquid metal boiler and, in general, these methods could lead to different superheat histories. In one method, called the all-liquid fill, the boiler is completely filled with subcooled liquid and the temperature is then raised until boiling begins. In this case, the initial vaporization process is constrained to begin at a location submerged in the liquid. In the other method of startup, called the two-phase fill, the boiler is only partly filled with liquid metal, so that the boiler contains an interface between the liquid and its vapor (or vapor inert gas mixture). In this case, the liquid may begin to boil immediately upon introduction into the system, if its temperature is sufficiently high and the inert gas residual pressure sufficiently low. The phase change may occur at the interface or at a location submerged in the liquid.

Experiments were performed in this program using both methods of fill, and with a wide range of fill liquid temperatures, inert gas levels in the system, saturation temperatures, and with two distinct levels of dissolved gas in the potassium. An electrically-heated tube test section was used to make the liquid superheat studies because this method allows more detailed temperature and heat flux information to be obtained than do alternate methods. Although electrical heating occurs in the liquid metal as well as the tube wall, this effect in the worst case of a completely filled tube is not serious. A detailed analysis of this heating method and its influence on radial temperature differences and other aspects can be found in the report.

One parameter which is very difficult to vary in an experiment of this type is the character of the boiler surface; roughness, surface cavity size and wall

contaminant level are fixed properties of a given test section. Because no generality in this regard could be attained in this program, an attempt was made to duplicate present day boiling liquid metal power plant practice in the preparation of the boiler tube. Consequently, the experimental results would at least be as applicable to boiler design problems as possible. For this reason the tubing chosen was niobium-1% zirconium alloy drawn tubing and contained a single vane helical insert of the same material. The cleaning methods used before the experiments were begun likewise duplicated present practice for boiling alkali metal systems.

The results of the potassium boiling inception study are presented in the following sections. Specifically, a description of the forced flow potassium boiling apparatus, the experimental procedure used, the results obtained, and interpretations of the results are presented. In addition, support information is presented in the appendices.

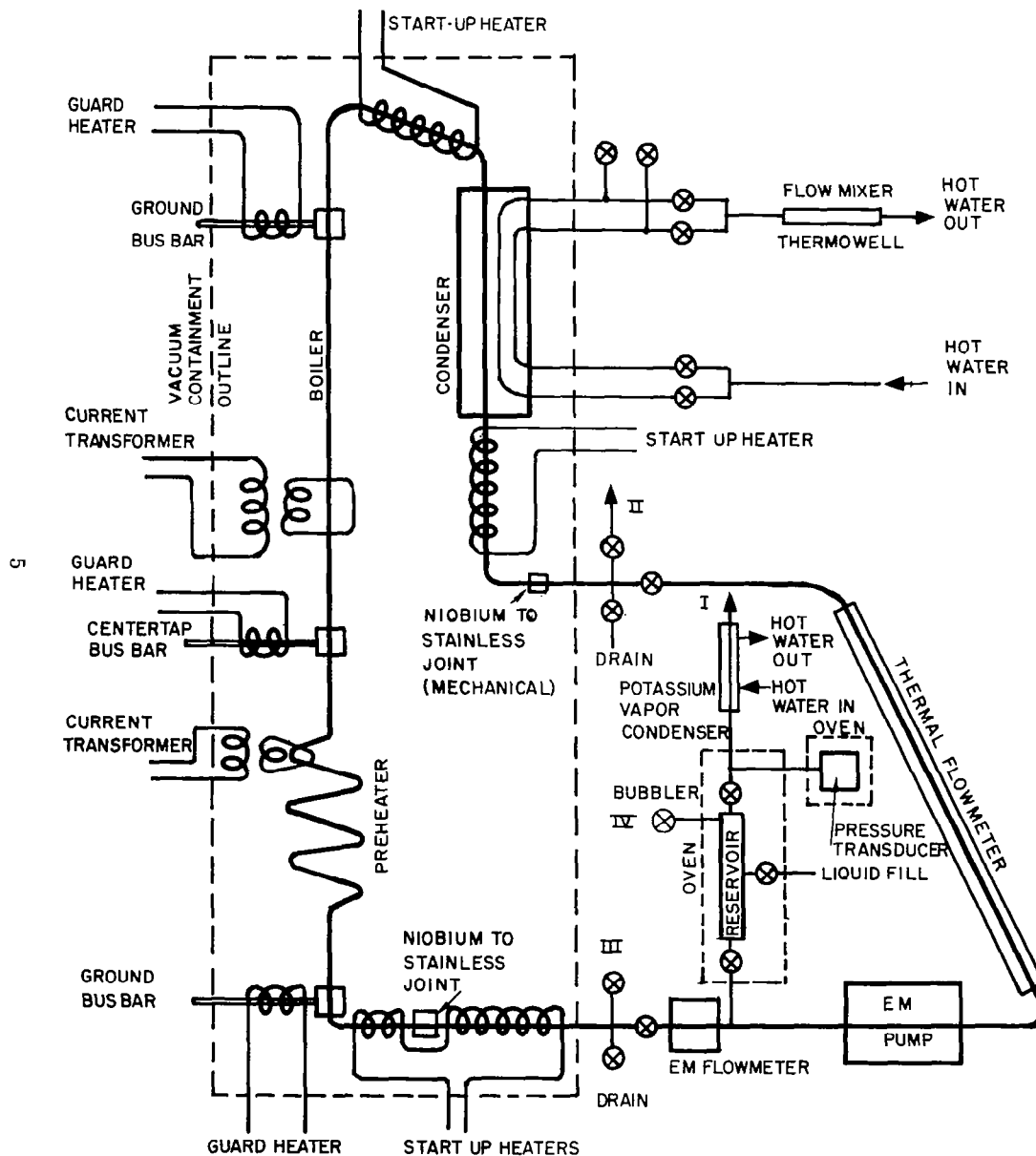
II. FORCED FLOW POTASSIUM BOILING SYSTEM

The forced flow potassium boiling system used for this program was adapted from an existing boiling liquid metal apparatus. The potassium circuit includes a preheater, boiler, condenser, thermal flowmeter, electromagnetic pump, electromagnetic flowmeter and potassium reservoir. A schematic diagram of this circuit and some of the accessory equipment is shown in Figure II-1.

The preheater, boiler, and condenser all contain refractory metal components and are enclosed in an evacuated chamber for protection from oxidation and for thermal insulation. Boiler and preheater power input is by direct electrical resistance heating, through three bus bars clamped to the tube. The AC current is added through the centertap bus located at the intersection of the boiler and preheater, divides and flows partially through the boiler, and partly through the preheater, returning to ground through the other two bus bars located at the extreme ends of the boiler and preheater. The boiler contains a helical vane insert.

All of the potassium circuit components external to the vacuum vessel are constructed of Type 316 stainless steel. Tubing unions form the bimetallic joints. Valve tees located near these joints are used for potassium draining, evacuation, gas charging and, in addition, allow decoupling of the boiler assembly for cleaning or repair without contaminating the remainder of the system.

The major components and accessories of this boiling liquid metal system and its instrumentation are described in the following sections.



Notes:

- 1) Points indicated with Roman numerals connect to similarly numbered points on manifold. (SEE FIG. II-11)
- 2) Start up heaters external to vacuum containment are not shown.
- 3) Electrical power is required for
 - a) preheater-boiler
 - b) guard heaters
 - c) start up heaters
 - d) EM pump
 - e) thermal flowmeter
 - f) reservoir oven
 - g) pressure transducer oven

Figure II-1. Schematic diagram of potassium circuit.

A. Potassium Circuit Components

1. Boiler and Helical Vane Insert

The boiler is constructed of a 0.25-inch outside diameter, 0.19-inch inside diameter niobium-1% zirconium tubing. It is 72 inches long, straight, and oriented for vertical upward flow, with the exception of the lower eight inches, which is sharply curved to allow motion for thermal expansion.

This tube is directly heated by passing an alternating current through the tube wall. The potassium liquid in the boiler acts as a current carrying conductor in parallel with the tube wall and the choice of a relatively thick-walled small diameter tube then allows most of the current to flow in the tube wall. (The appendix to this report contains an analysis of the error incurred in fluid temperature measurement due to resistance heating in the potassium.)

The boiler contains a helical vane insert which extends almost the full length, stopping short of the bus bars at each end to avoid electrical current transfer problems. It is constrained in place by friction. The helical vane was constructed slightly oversize, then pulled into the boiler so that when the tension was released it sprung tightly against the inner wall.

The helix was constructed in 16-inch sections by close-wrapping a square niobium-1% zirconium wire around an oversized mandrel, and then pulling the coil axially to obtain the desired pitch to diameter

ratio of 2.0. This P/D ratio was representative of full-scale potassium boilers. The sections were then welded together to form a continuous length of 71 inches. Other dimensions of this component are given in Figure II-2. The insulated boiler is visible in Figure II-3.

2. Condenser

The condenser is a portion of the continuous length of niobium-1% zirconium tubing which includes the preheater and boiler. The condenser portion of the tube is cooled by clamping a hot-water jacketed stainless steel assembly onto the outside.

Figure II-4 is a full-scale drawing of the clamp-on condenser assembly, showing the method of construction. This unit uses water at 160° to 200°F to condense potassium at 1400° to 2000°F; the heavy stainless steel clamp bars create a thermal resistance for this circuit. The geometry of these bars provides a heat flow path long enough to prevent film boiling of the water, which would render the condenser ineffective. The space between the two clamp bars, although small, is adequate to prevent significant heat flow between the two bars, so that the heat flow path is well defined.

The water side tubes have been flattened to decrease their flow area and increase water flow Reynolds numbers, so that adequate water side heat transfer conductances are obtained with flows small enough to give a readily measurable water temperature rise. The combination of water side wall area and conductance is adequate to prevent local subcooled boiling of the water under heat flow conditions compatible with the maximum power available to the system.

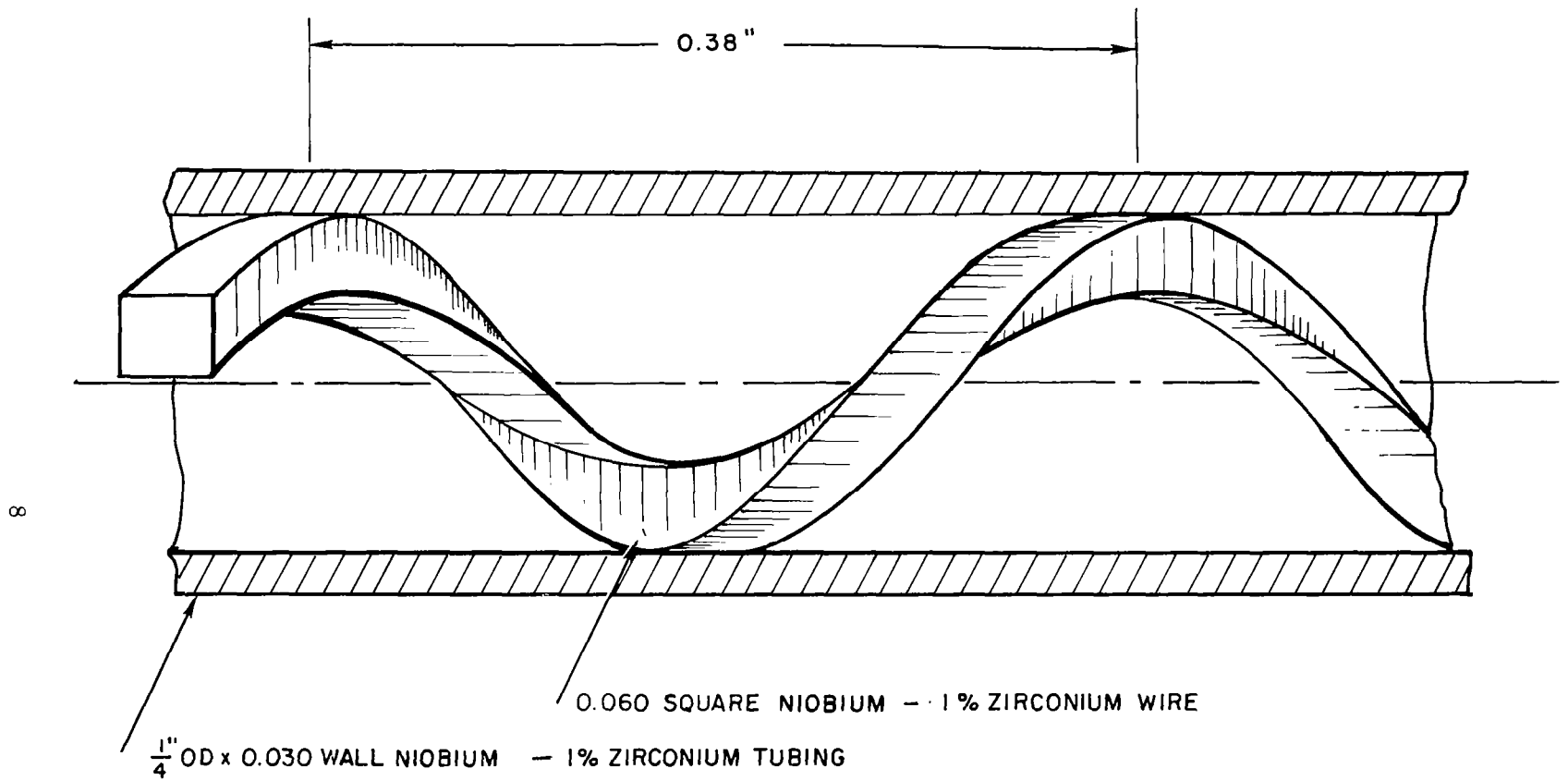


Figure II-2. Helical insert (not to scale).

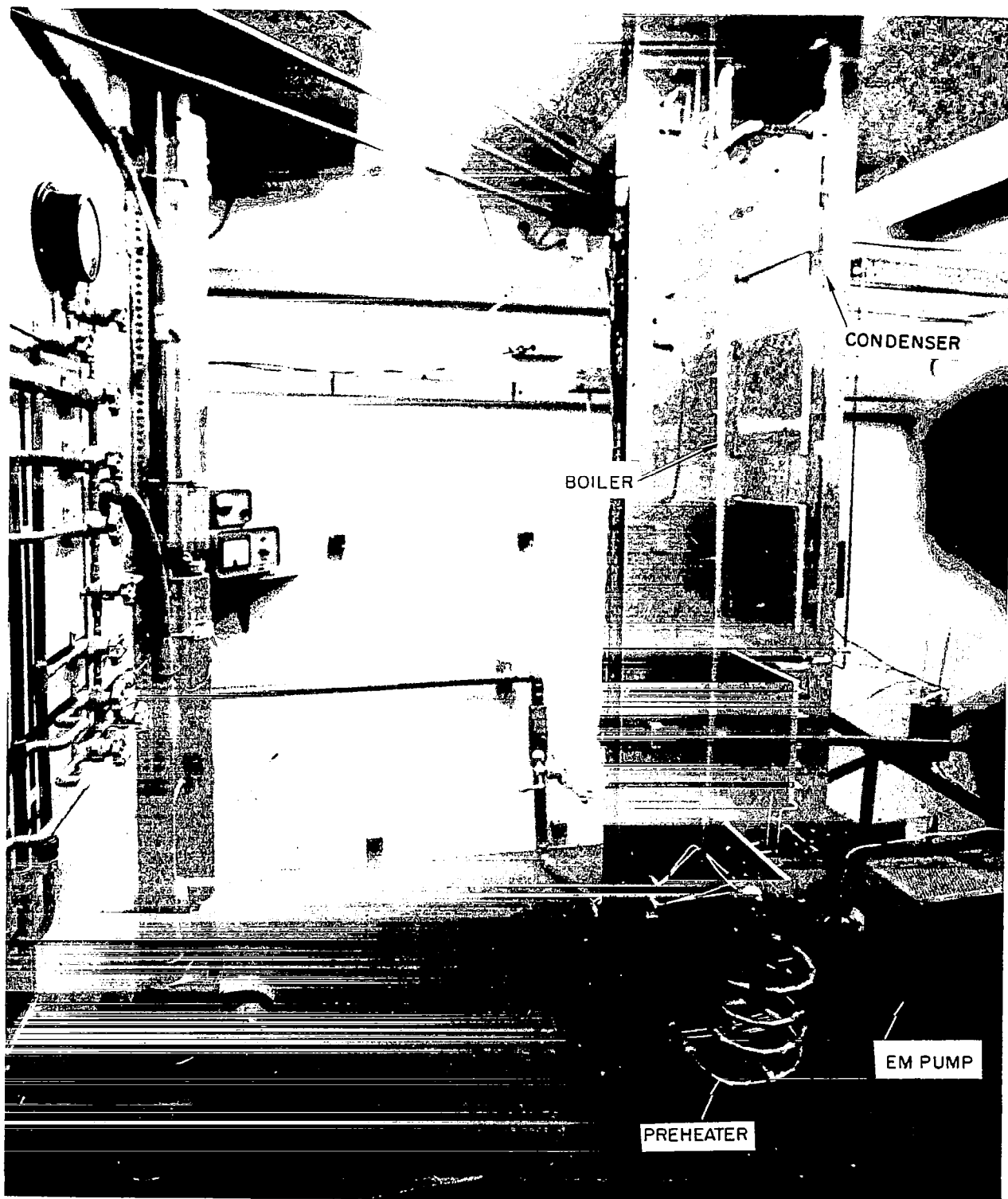


Figure II-3. View of boiling inception apparatus with vacuum housing removed.

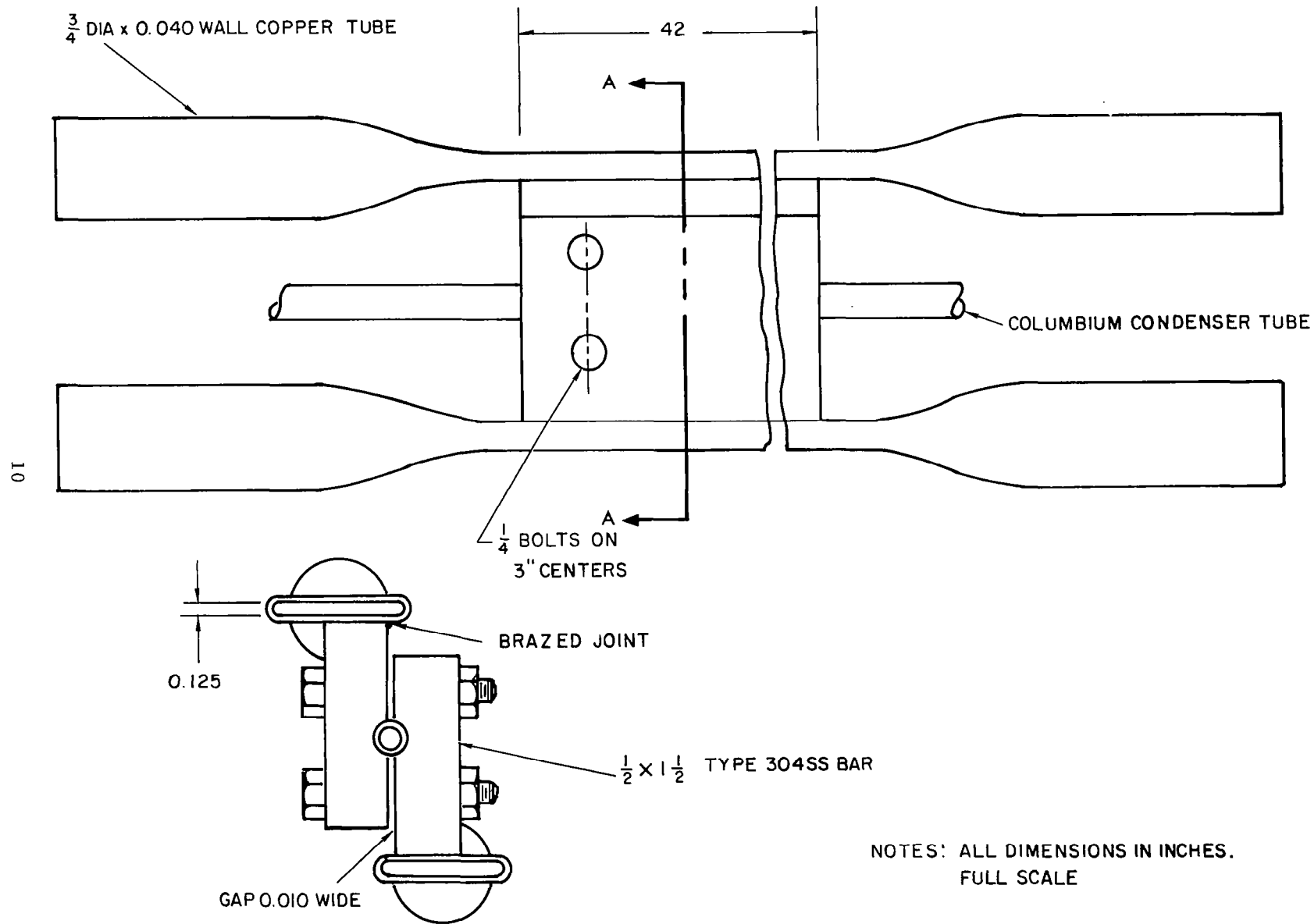


Figure II-4. Clamp-on condenser assembly.

3. Preheater

This unit is a portion of the continuous length of tubing which makes up the entire high temperature section of the potassium circuit. It is 72 inches long and is formed into a helical coil to conserve space in the vacuum chamber. The insulated preheater is visible in Figure II-5.

4. Preheater-Boiler Electrical Bus Bars

These items are constructed of nickel rod, with Haynes 25 clamping caps and bolts. The niobium tube is clamped along a 1/2-inch length by each of these bars. It has been shown in other programs¹ that niobium mechanical properties deteriorate due to diffusion of metallic contaminants into niobium at elevated temperatures. Therefore, these clamp-on bus bars have been provided with refractory metal sleeves in order to protect the niobium boiler from the nickel electrodes. The insert material used is pure tantalum, rather than niobium-1% zirconium. It was felt that the pure tantalum would provide better protection. The centertap and lower ground bus bars are visible in Figure II-5.

5. Insulation

The preheater-boiler condenser assembly has been clad with three layers of dimpled niobium radiation shielding. This covering provides

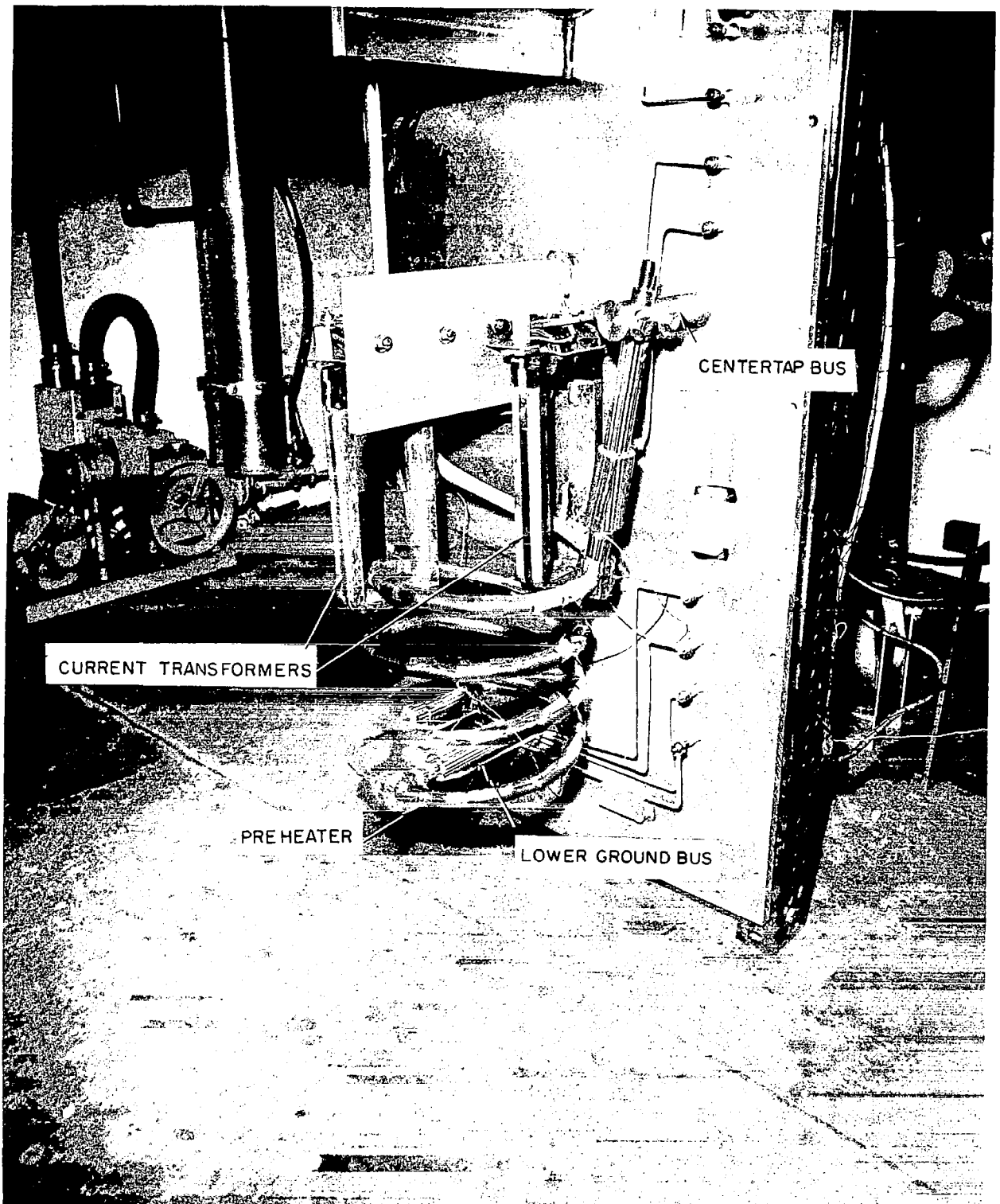


Figure II-5. View of lower end of potassium circuit with vacuum housing removed.

some oxidation protection as well as thermal insulation. The clamp-on power electrodes and the condenser water tubing have also been equipped with radiation shielding, in this case alternate layers of corrugated and flat stainless steel sheet. The multilayered radiation shield over the boiler could carry a significant portion of the heating current if metal-to-metal contact were allowed, so that heat fluxes to the potassium would not be well determined. To prevent electrical conduction in the shields, they have been insulated from the preheater-boiler by slipping short lengths of high-purity alumina tubing (Coors AD99) over the boiler tube, and then placing the radiation shields over the alumina. Slots were cut in the alumina to allow passage for the thermocouple and voltage tap leads.

6. Vacuum Chamber for Refractory Metal Protection

The boiler container, which is a welded aluminum box 8-1/2 feet high, 1-1/2 feet wide, and one foot deep, is shown in Figure II-6. The flat "cover" of the container is installed vertically in a double-walled steel room, and the container itself is suspended from a trolley on the ceiling, so that it may be rolled back out of the way. All of the thermocouple feed-throughs, power lines, bus bars and other vacuum penetrations are made through the flat cover and the preheater-boiler-condenser assembly hangs from brackets on the inside of the cover as well. This arrangement was made so that it was possible to completely assemble and instrument the test boiler while the container cover was lying on a work bench outside the steel room, to simplify the process of assembling the refractory components and their accessories.

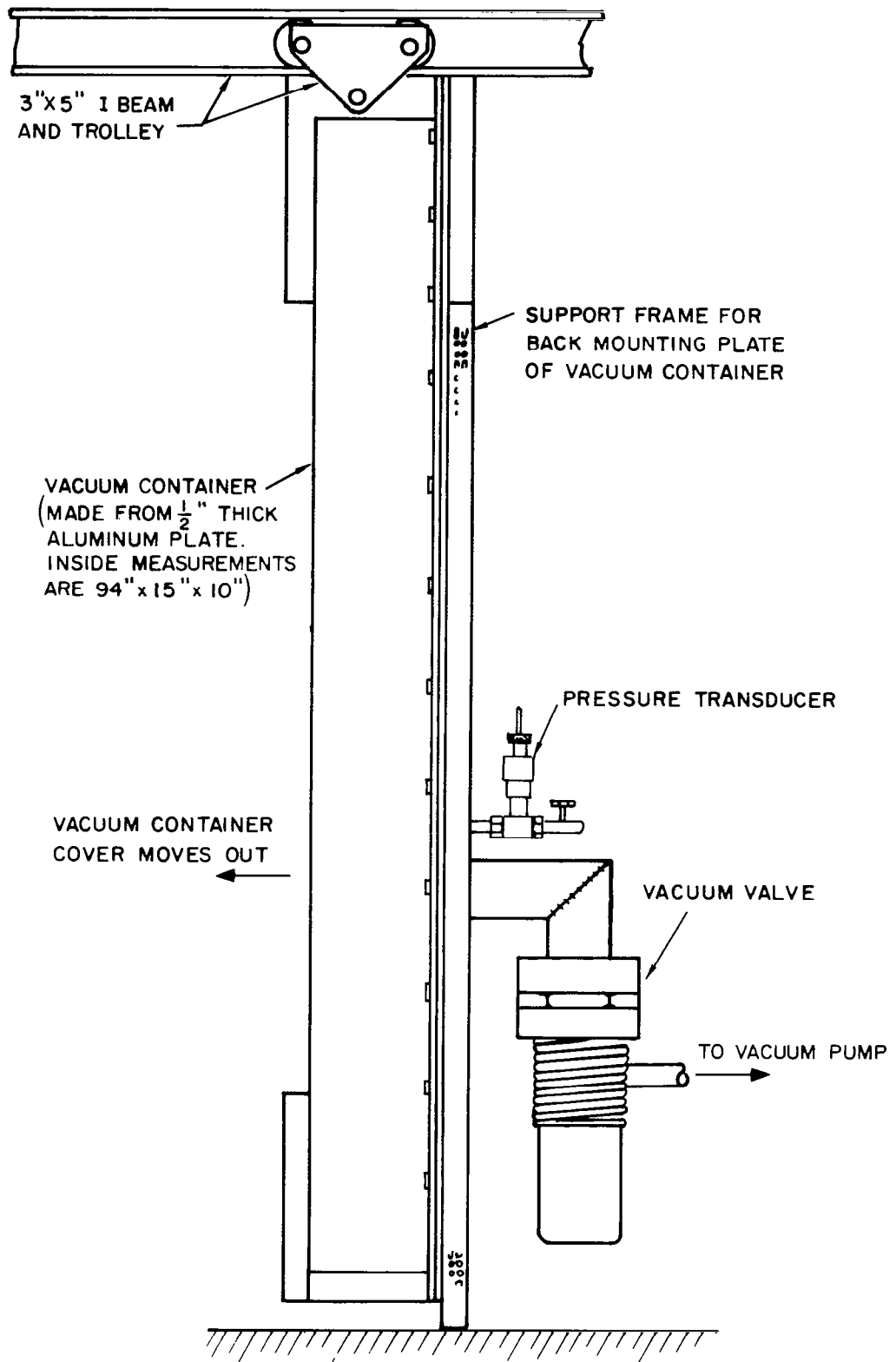


Figure II-6. Vacuum housing for liquid metal boiling system.

The vacuum chamber is evacuated by means of a six-inch oil diffusion pump and 46 cubic-foot-per-minute mechanical backing pump. These units are coupled to the chamber through a six-inch vacuum gate valve. Vacuum instrumentation for the chamber is provided by a thermocouple gage and discharge gage installed in the backing plate. The chamber is also provided with an argon supply so that it can be inert-gas filled when experiments are not taking place. This process prevents contamination of the vacuum vessel by air leaks, and decreases the pump-down time to a few hours. The chamber is equipped with a vacuum-tight relief valve set for one psi, so that the chamber cannot be accidentally pressurized to a dangerous level. The diffusion pump, valve, and chamber instrumentation may be seen in the photograph of Figure II-7.

A schematic drawing of the backplate of the vacuum chamber, showing the location of various components and chamber penetrations, is presented in Figure II-8.

7. Vacuum Feed Throughs for Liquid Streams

In addition to the commercially-available electrical feed throughs used in the vacuum chamber wall, there are six special thermal insulation feed throughs. The system fill procedure requires that the potassium be introduced into the system at several elevated temperatures, and since the liquid must pass through the wall of the aluminum environmental chamber, special thermal insulation feed throughs are required. These are designed to have a flexible stainless steel membrane

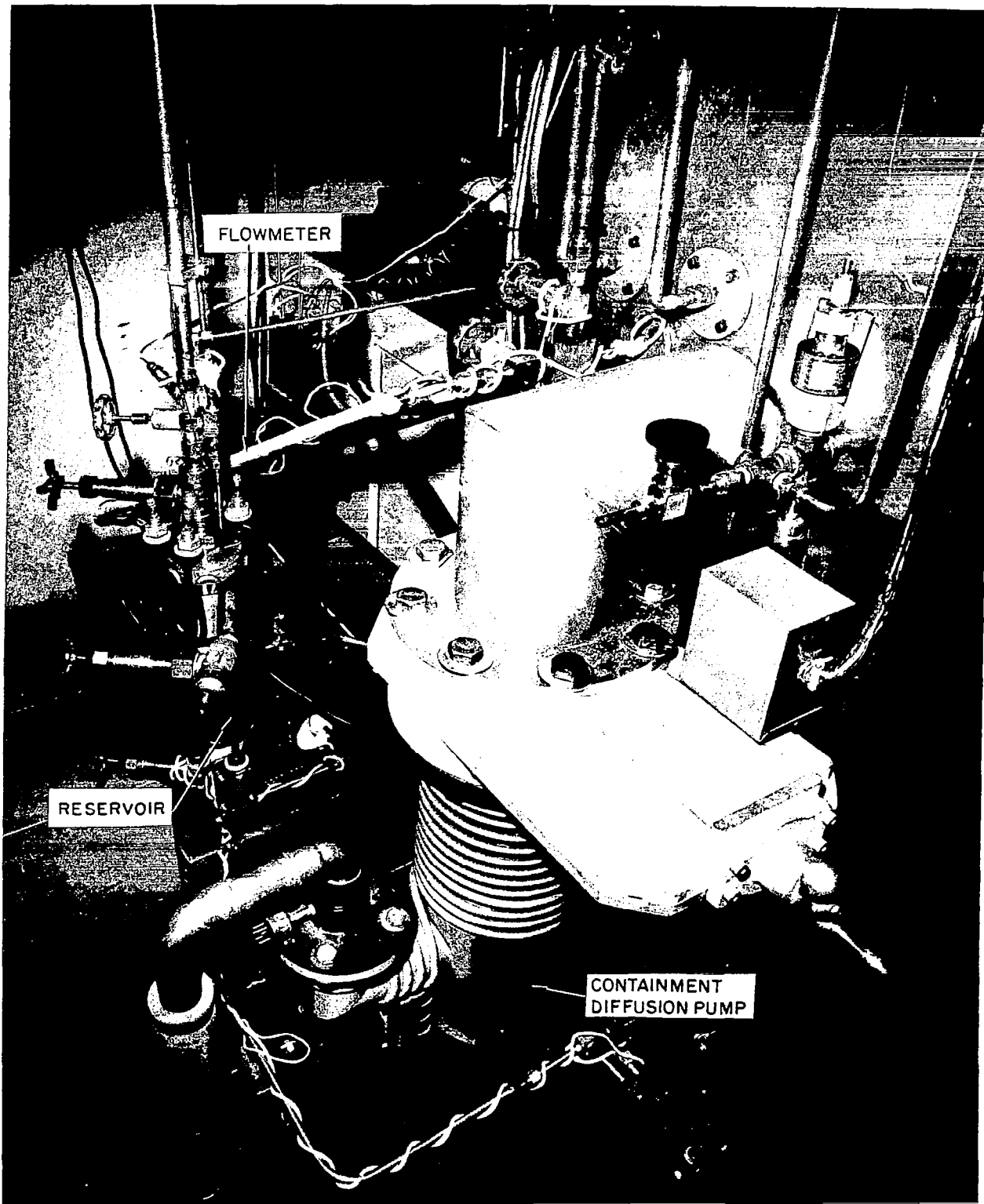
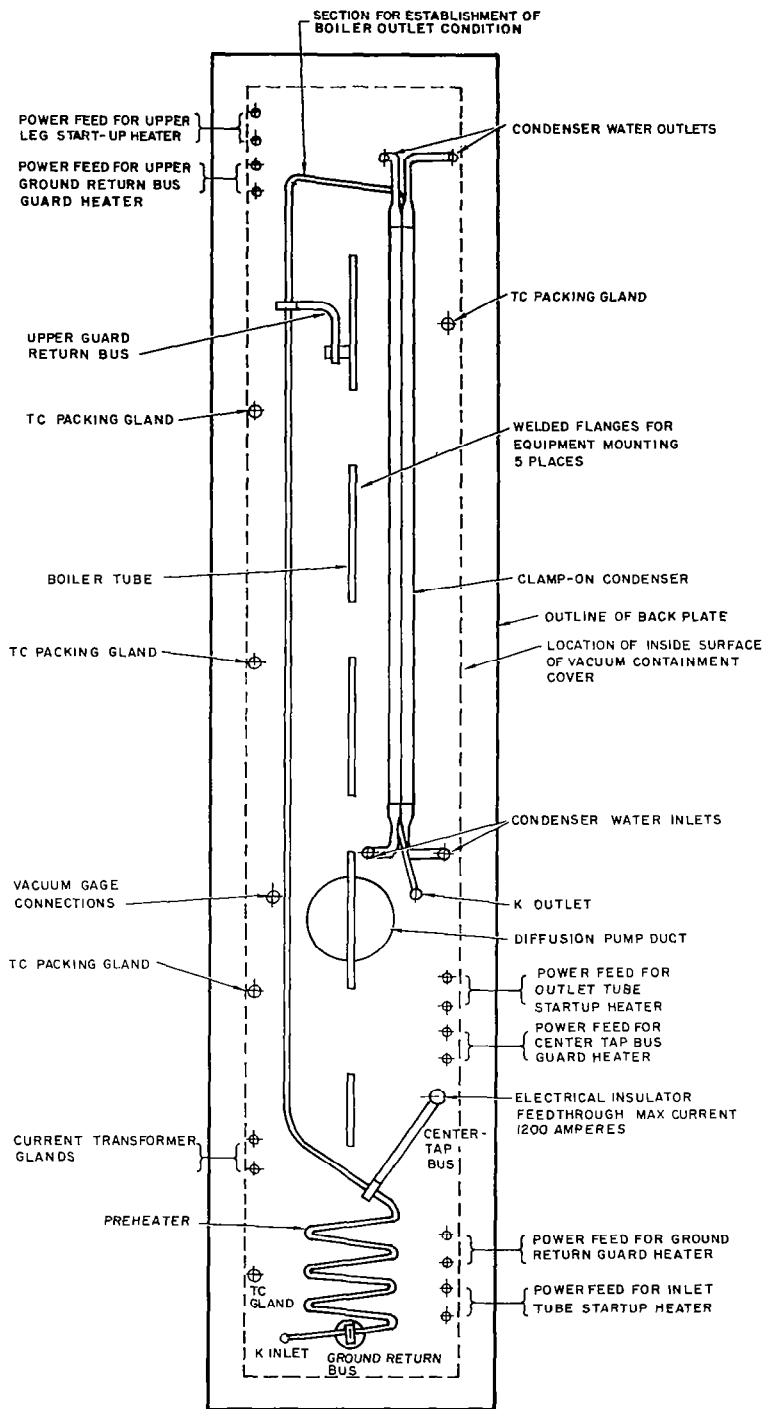


Figure II-7. View of potassium circuit outside vacuum containment.



Notes:

- 1) Each TC packing gland carries eight thermocouples (16 wires)
- 2) All liquid flow lines pass through back plate in thermal insulators
- 3) Boiler and preheater shown without instrumentation, or thermal radiation shields

Figure II-8. Inside face of vacuum containment back plate, showing placement of major components.

with a long thermal path between the potassium circuit tubes and the aluminum wall. The flexibility is required to relieve tubing strains and to avoid thermal shock failures during filling. A drawing of these components is shown in Figure II-9. These units are also installed on the condenser water inlet and outlet lines, so that water mixing processes and temperature measurements can be performed outside the environmental chamber.

8. Guard Heaters and Trace Heaters

Each of the preheater-boiler electrical bus bars is provided with a guard heater, and many sections of the potassium tubing are provided with start-up heaters. These heaters consist of 0.030-inch diameter Nichrome wire, insulated with alumina "fish spine" beads. The heaters are in suitable lengths to provide a match with the auto-transformer power supplies and are wrapped around the bar or tube and wired in place. These heaters do not outgas seriously into the vacuum container even at operating temperatures, and have proved satisfactory in the experiments.

The trace heaters along the columbium tubing, which are required to start the system, have been installed over the columbium radiation shielding so that they do not impair the protection for the tube, and overlaid with stainless steel foil. There are three of these heaters, one below the preheater on the potassium inlet line, one between the boiler and condenser, and one on the outlet line below the condenser.

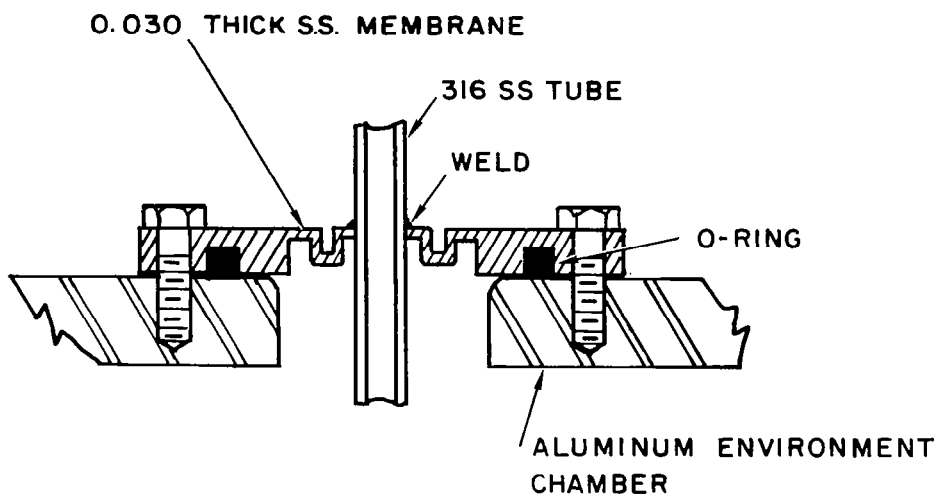


Figure II-9. Thermal insulation vacuum feed through with flexure ring.

9. Supply Reservoir

This reservoir may be isolated and charged with potassium separately from the remainder of the system. Full, it contains approximately two pounds of potassium, enough so that the potassium circuit can be drained and recharged four times. The supply reservoir and its associated valves are enclosed in an elevated temperature oven, heated with three Calrod units of 1000 watts each, curved to fit around the 3-1/2 inch diameter (outside) reservoir. These heaters are controlled by an autotransformer, rather than an automatic on-off type controller. Past experimental programs have shown that power pulses from on-off controllers for this much power can effect the records of some of the transient recording equipment due to coupling through the laboratory power systems and the steady current of the autotransformer will not.

The potassium reservoir oven is required for a number of operations. One of these operations is system filling, which is accomplished using liquid from the reservoir at temperatures up to 1200°F. The oven heats the reservoir and its contents to this temperature. Another operation is liquid degassing, which is performed by boiling at reduced pressure. Other operations include filling; all-liquid fill testing, during which the supply reservoir serves as a surge tank; and saturation of the potassium with argon gas by bubbling.

The line leading from the supply reservoir to the gas manifold is equipped with a three foot long jacket through which water from the

hot water system may be circulated. This jacket serves as a vapor condenser during the degassing process, and since it is maintained above the potassium melting point, keeps the line from plugging during degassing, and potassium saturation with argon. This line serves as the argon return vent during the process of bubbling gas through the potassium, and is subject to splashing and liquid entrainment from the reservoir. A number of these features can be seen in the photographs of Figures II-7 and II-10.

The preceding list of items includes the major components of the potassium circuit, with the exception of instrumentation. There are several major auxiliary systems used in the operation of the system. These systems are described in the following section.

B. Auxiliary Operating Systems

1. Argon and Vacuum System

Figure II-11 contains a schematic diagram of the argon and vacuum control manifolds for the interior of the potassium circuit. This complex valving system will allow all operations such as filling, degassing, draining, and pressurizing to be accomplished without decoupling any lines. The possibility for introducing contamination into the system is, therefore, minimized.

This manifold also permits sensing of vacuums in remote parts of the circuit. Argon charging levels below atmospheric pressure are accomplished by means of a balance between the vacuum pump and the small argon metering valve (No. 30).

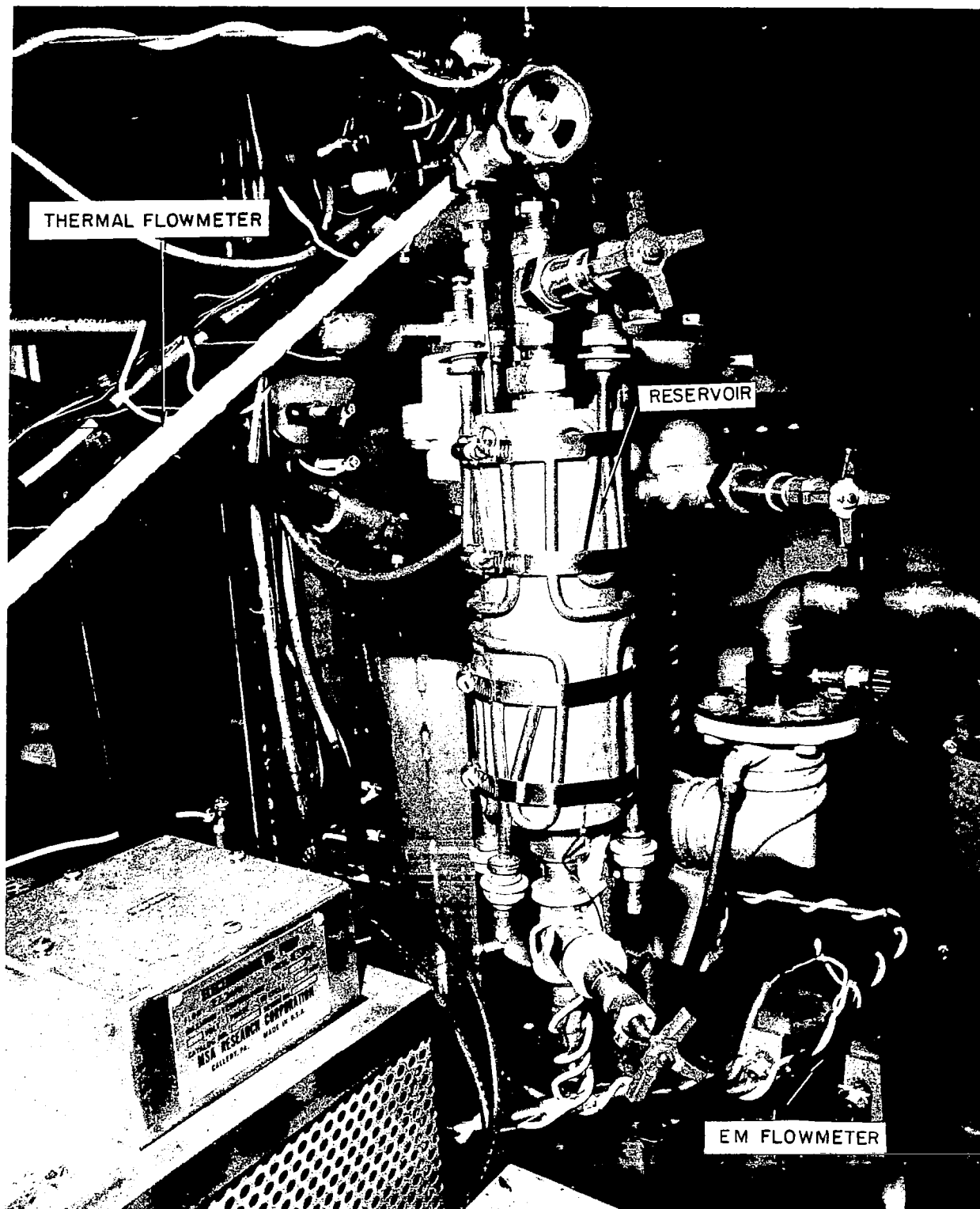


Figure II-10. View of potassium circuit components outside vacuum containment.

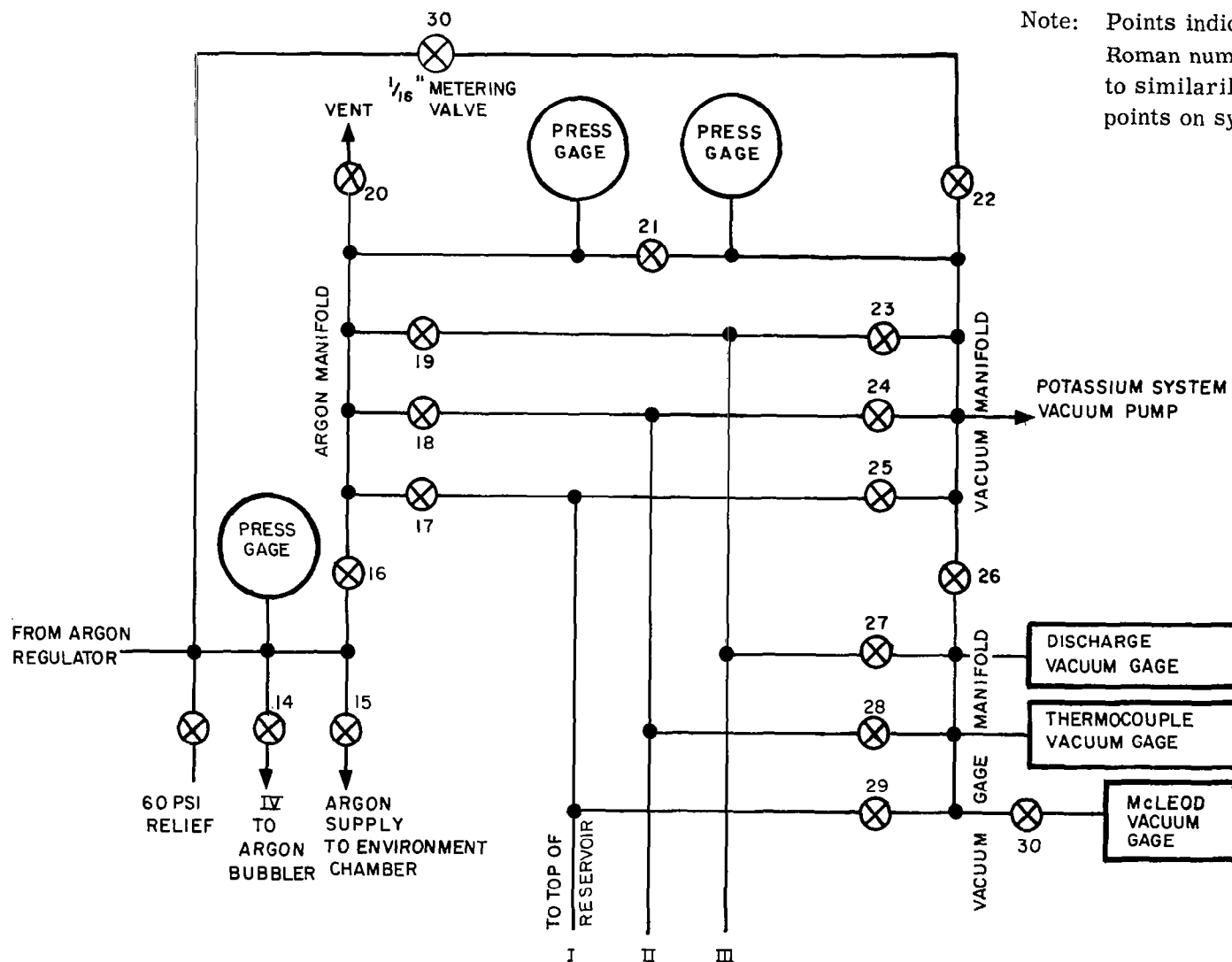


Figure II-11. Argon and vacuum control manifold diagram.

Vacuums below 10^{-5} millimeters of mercury can be obtained at the most distant points in the circuit with reasonable pumpdown times. A photograph of this manifold is shown in Figure II-12.

2. Hot and Cold Water Systems

Hot water above the melting point of potassium is used for cooling the condenser, and for preheating it before system start up. The hot water supply is also used for temperature control of the water jacketed line between the potassium reservoir and the gas control manifold. Since the major portion of the heat added to the potassium during experiments is rejected to the condenser water, means must be provided for cooling the hot water. This is accomplished by rejecting the heat through a water-to-water heat exchanger cooled with the civic water supply. The building water supply is also used to cool the vacuum chamber diffusion pump.

A schematic diagram of the water system is shown in Figure II-13.

3. Electrical Power System

Electrical power is supplied through two main circuits, a 100 ampere, 220 volt single phase line; and a 50 ampere, 220 watt single phase line. The 100 ampere line supplies only the preheater-boiler power, through a saturable-reactor controlled step-down transformer, combined into a single unit. The reactor-transformer is a Harder Company power supply rated at 27.5 kva (2200 amperes at 17 volts). Power from this supply is conducted through short copper bus lines to the vacuum chamber.

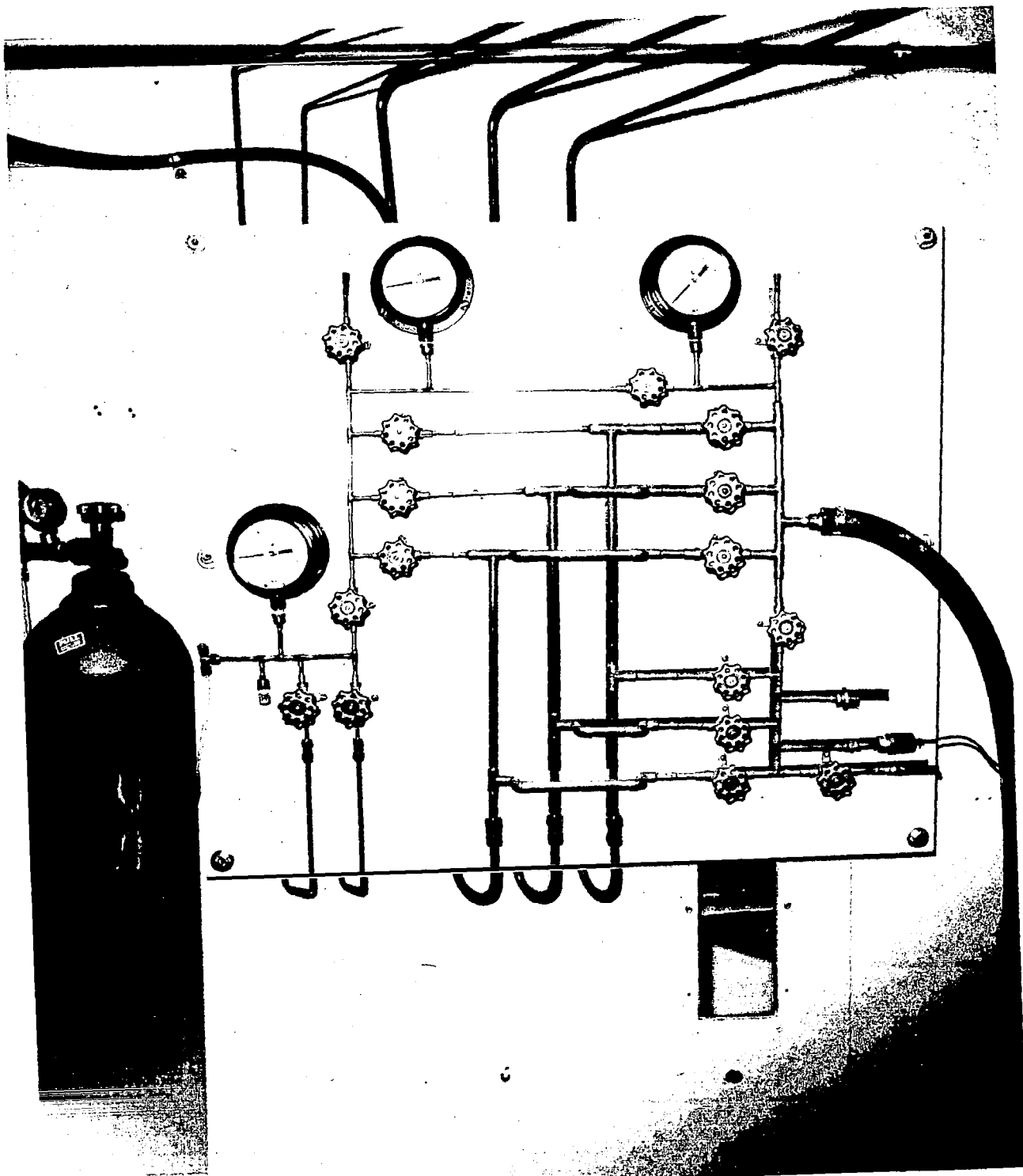


Figure II-12. View of inert gas handling manifold for potassium circuit.

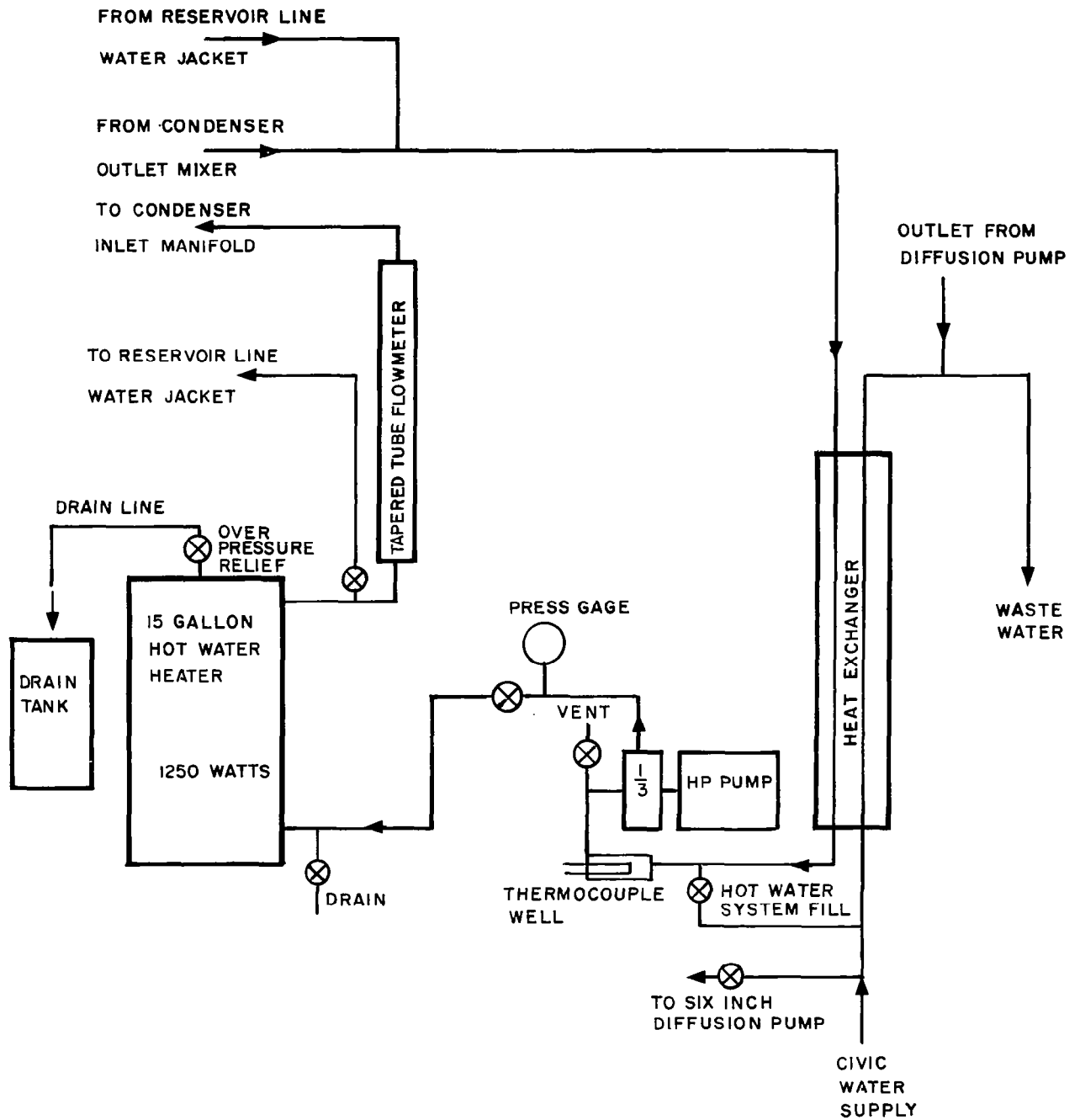


Figure II-13. Hot and cold water systems.

There is only one electrical feed through for the preheater-boiler current. The ground return at the ends of the boiler and preheater are fastened directly to the aluminum vacuum chamber, and the chamber backing plate acts as the electrical conductor. Therefore, one of the power supply lines is fastened directly to the chamber. The centertap line passes through a specially-constructed vacuum feed through rated at 3000 amperes.

The 50 ampere, 220 volt power line is used to supply a circuit breaker system, from which it is distributed to the following circuits, both 110 volt and 220 volt.

- a. Preheater inlet heater
- b. Lower ground bus guard heater
- c. Centertap bus guard heater
- d. Upper ground bus guard heater
- e. Boiler outlet start up heater
- f. Condenser outlet start up heater

Circuits a. through f. enter the vacuum chamber through electrical power feed throughs, and are each controlled by 9 ampere variable autotransformers.

- g. Water heater
- h. Water pump
- i. Electromagnetic pump control autotransformer
- j. Pressure transducer oven
- k. Thermal flowmeter (through a 30 ampere variable autotransformer)

- l. Start up trace heaters (through a 9 ampere variable autotransformer)
- m. Electromagnetic pump start up heater
- n. Potassium reservoir oven (through a 20 ampere variable autotransformer)
- o. Auxiliary electrical panel in double-walled room for instruments, miscellaneous small equipment, and six inch diffusion pump.

C. Instrumentation

1. Test Section Instrumentation

a. Thermocouples

The test section temperatures are determined by 27 thermocouples, distributed so that there are five on the preheater, three on the bus bar clamps adjacent to the tube, and 19 on the boiler itself. All but two of these are Chromel-Alumel, and are spotwelded directly to the niobium tube. The remaining two, which are both toward the upper end of the boiler, are tungsten-rhenium thermocouples. (The specific alloys are W 3% Re and W 25% Re.) These latter have been included as a check on the base metal thermocouples. There is the possibility that at elevated temperatures in vacuum, where the chromium in base metal thermocouples may be expected to evaporate, that the calibration would shift with time. Such a shift (which did not appear to be significant during the test program), could be detected by comparison with the tungsten-rhenium thermocouples.

In addition to the thermocouples on the preheater-boiler assembly, there are many others located throughout the system, specifically, 52 Chromel-Alumel thermocouples and four tungsten-rhenium thermocouples.*

The tungsten-rhenium thermocouples are, of course, not spot-welded to the niobium tube, but are mechanically fastened by

*All thermocouples were calibrated in place at room temperature, and run at the maximum hot water system temperature of 190 °F.

clamping tabs of thin niobium sheet, which are spot-welded securely to the tube. Tabs of this type are also used to support the two-hole ceramic insulators which are used on the first one and one-half inches of all of the boiler-preheater thermocouples, in order to carry the wires out through the radiation shielding. All of the thermocouples have been dressed halfway around the tube at right angles to the tube axis, before bringing them out through the insulation. This was done to minimize lead conduction errors.

b. Current Transformers

The heating currents in the preheater and boiler are measured by two specially-constructed current transformers placed in the vacuum chamber. The laminated iron loops in the current transformers surround the heated tube outside of the insulation.

Although the insulation is quite effective, the possibility of overheating the current transformers by radiant energy exists. One would not expect this radiant energy to damage the current transformers, but the heating could possibly cause them to outgas into the vacuum. These units are, therefore, clamped solidly to the aluminum vacuum chamber, which acts as a heat sink.

Output of the current transformers passes through insulated vacuum feed throughs to panel meters outside the steel room. This current measuring system has been calibrated by use of standard shunts.

c. Voltage Distribution

The voltage distribution along the test section, which is used to determine not only power distribution, but liquid distribution as

well, utilizes the Alumel leg of each thermocouple as a voltage tap. After the thermocouple leads pass through the packing glands to the outside of the vacuum chamber, a copper lead wire system for the voltage is connected to the Alumel leads. This set of wires enters a switch box which allows connection of each lead in turn, so that the AC voltage distribution along the boiler may be determined. Some of these leads are also connected to the voltmeters in the liquid level measuring system.

2. Potassium Flow Rate

a. Thermal Flowmeter

This unit consists of a 46-inch length of 3/8-inch OD stainless steel tubing uniformly wound with a resistance heater, and heavily insulated. It is instrumented with six thermocouples and accurate electrical power measuring equipment, so that the heat input to the potassium and the consequent temperature rise may be accurately determined. Heat losses from this section were measured as a function of temperature level and found to be less than 25 percent of the heat input to the fluid at the lowest flow rate. Mean flow rates can be measured within an accuracy of a few percent by this method. This instrument, shown without its insulation, may be seen in Figure II-10.

b. Electromagnetic Flowmeter

This unit consists of a large permanent magnet with flux concentrating pole faces, placed around the preheater inlet line. The output is sensed by two spotwelded voltage taps at right angles to the pole

faces. The output of this instrument is recorded on a Sanborn oscillograph, together with the output of a thermocouple in the upper section of the boiler. This record provides a history of the flow during the entire run, as well as a relationship between flow aberrations and temperature changes in the boiler. The electromagnetic flowmeter is calibrated during steady, non-boiling flow, using the thermal flowmeter as a standard. Under boiling conditions the flow tends to fluctuate rapidly, and the electromagnetic flowmeter follows the flow variations accurately. The thermal flowmeter yields only an average flow rate under these conditions since it is massive and its temperatures respond relatively slowly to variations in flow. The electromagnetic flowmeter may be seen in Figure II-10.

3. *Temperature of Fluid Discharged from Boiler*

The condition of the fluid discharged from the boiler is determined from a special section of the niobium tube between the boiler exit and the condenser inlet. This section of tubing is heavily insulated and has a guard heater over the outside of the insulation. There are six thermocouples placed along the length of this section; two tungsten-rhenium, and four Chromel-Alumel. Since the flow from the boiler may be a saturated mixture of the two phases, or superheated liquid or vapor, a single thermocouple does not necessarily represent the fluid condition accurately. Records of the complete set of thermocouples establish the boiler outlet temperature and its decay toward equilibrium as mixing takes place.

4. Potassium Circuit Pressures

Pressures are measured at two different locations in the potassium circuit, using Pace Engineering variable reluctance bridge-type differential pressure transducers. The transducers are located on the reservoir and at the inlet to the pump. The outputs of these two transducers are recorded on a two-channel Brush oscillograph.*

In order to obtain adequately detailed pressure information, relatively sensitive pressure transducers (± 5 psi full scale, and ± 15 psi full scale) were used with considerable amplification, and the total span of pressures in the system can exceed the range of the recorder. Although this condition would not damage the equipment, it would eliminate the pressure record. In order to prevent this occurrence, provisions were made for applying a steady, known pressure on the side of the pressure transducers not connected to the potassium circuit. This bias pressure was adjusted to keep the transducer-readout system within range.

The pressure transducers are contained in a temperature controlled oven. This oven is required to maintain the potassium in the transducers in a molten state, and to hold the environmental temperature of the transducers nearly constant. Although these instruments have relatively small calibration drift due to ambient temperature variation, the system pressure is a crucial parameter and instrument artifacts from ambient temperature variation must be minimized. The oven used is a copper box containing a 50-watt heater which is controlled

* The electronic pressure gages were calibrated with the Bourdon tube gages on the argon manifold.

by a liquid bulb thermostat to $180^{\circ}\text{F} \pm 1^{\circ}\text{F}$. The thermal oscillations of the transducer itself when in this oven are on the order of $\pm 0.2^{\circ}\text{F}$ since it is a large mass, insulated from the oven by an air space. Pressure transducer calibration drift due to temperature effects is negligible.

5. Condenser Heat Flow Instrumentation

The heat flow in the condenser is required in order to establish energy balances for the system. Since the condenser is water-cooled, and its heat losses to the surroundings are negligible, the water flow and temperature rise establish the heat flow.

The water streams in and out of the condenser are measured with single thermocouples in wells. The inlet stream, which comes through a long run of insulated pipe with several bends and flow control valves, is well mixed when it reaches the inlet thermocouple well. The condenser outlet water must, however, be carefully mixed. The condenser has two separate water cooling tubes, and since the flow in these two tubes is not usually exactly matched, these two streams have different outlet temperatures. They are, therefore, passed through a flow mixer before the outlet water temperature is measured. This flow mixer consists of a length of tubing with six baffles extending halfway across the tube from alternate sides. The water flow through this section is very turbulent and at the outlet is thoroughly mixed.

The water flow rate is measured with a tapered tube flowmeter.

6. Liquid Level and Vapor Quality Indicator

A liquid level sensing system was designed and used in the forced flow boiling system. Specifically, six high-impedance, low-voltage AC voltmeters were used to measure six adjacent voltage drops along the boiler length. On the basis of the tube geometry and the electrical resistivities of the tube, insert and molten potassium, it can be shown that the electrical resistance of an empty tube is about 2.5 times greater than the value for a tube filled with liquid potassium.

When using the voltmeter assembly to measure the liquid level in the boiler (while initiating a two-phase flow experiment) twofold voltage drop reductions at a given station indicated that liquid potassium had filled that station.

When the liquid superheat experiments were in operation, one could also observe changes in vapor quality by noting the transient behavior of the voltmeters. For example, when a vapor flashing excursion occurred (subsequent to liquid superheating), increases in voltage along the length of the boiler were observed as the vapor was formed. Motion pictures of the transient response of the voltmeters, together with an electronic timer under such circumstances, were taken. In addition, the corresponding, momentary flow reversals were noted on electromagnetic flowmeter traces and from transient wall temperature measurements in the preheater and boiler.

III. OPERATIONAL PROCEDURES

A. Component Cleaning Procedures

All stainless steel components in contact with potassium or used in the vacuum systems were degreased, and then cleaned before assembly with a pickling solution. This water solution, which contains hydrofluoric, nitric, and sulfuric acids, was followed by rinsing and wiping in domestic water with a final rinse in distilled water. Parts were dried with an argon stream. Bellows valves, and other complex parts which had been utilized in previous liquid metal programs, were heated in a high vacuum before the initial degreasing process in order to distill off any trapped liquid metal which might be contained in cavities which cannot be visually inspected.

All of the niobium-1% zirconium components were acid cleaned according to procedures used elsewhere to clean niobium parts for alkali metal systems.¹ The acid dip solution was made up of 48% concentration hydrofluoric acid, 70% concentration nitric acid, and distilled water in a 1, 1, 3 parts by volume solution. This acid dip was followed by a hot domestic water rinse and scrub, a distilled water rinse, and air drying. Pressurized argon was used for drying the tubular components.

After assembly of the system, it was evacuated and heated until a vacuum of 10^{-4} torr could be maintained. This heating cycle was also used to make heat loss measurements on the preheater, boiler, condenser, and thermal flowmeter insulation.

During all periods that the system has not been in operation, it has been maintained under argon pressure to prevent air and other contaminants from leaking into the potassium circuit.

B. Rinse Fill

The initial charge of potassium into the circuit was a rinse, using high purity potassium. To accomplish this task, the reservoir was filled with potassium while isolated from the flow circuit. The flow circuit was evacuated to 10^{-4} torr and heated to 300 - 350°F. The top of the reservoir was pressurized with argon, and the bottom valve opened to allow potassium to flow into the circuit and fill it completely. This charge was circulated for several hours. During this period, various items of instrumentation and equipment were tested and the electromagnetic flowmeter was calibrated by use of the thermal flowmeter. The flow circuit and supply tank were then drained completely, pressurized with argon above atmospheric pressure, and cooled.

C. Setting the Dissolved Gas Level in the Potassium

The two extremes of dissolved gas level in the potassium fill liquid; i. e., degassed and saturated, have been employed in the experiments. The procedures for achieving these conditions are described in the following paragraphs.

1. Degassing of Potassium

The most effective means of removing dissolved gases from liquids involves boiling, and it was intended to use this technique to degas the

potassium before charging the circuit. However, continuous boiling could not be maintained. Under conditions of reduced pressure and elevated temperature, the potassium in the reservoir could not be induced to boil, but superheated far above the saturation temperature. A change of phase of the large mass of liquid in the reservoir under these conditions would have been expected to drive potassium throughout the argon and vacuum interconnections, and possibly rupture some lines as well. The degassing procedure used was to hold the liquid metal at 1000°F or higher in the reservoir and to maintain the argon gas above the liquid at a pressure slightly less than the saturation temperature for a period of one hour. Under these conditions, the potassium vaporizes rapidly from the upper surface and strong natural convection cells are set up in the bulk liquid. However, there are no vapor bubbles generated. After one hour under these conditions, the potassium was considered to be degassed.

2. Saturation of Potassium

From Reference 2, it appears that the solubility of argon in potassium increases with increasing temperature. Therefore, it is appropriate to introduce the argon into potassium at elevated temperature; the procedure used is to heat the potassium in the reservoir to the fill temperature, and then to bubble argon through the liquid for a period of one-half hour. There is a submerged tube in the reservoir, placed near one wall, with the opening against the bottom of the reservoir. The rising bubbles should cause strong circulation in the liquid to mix it thoroughly. In this case, the argon pressure above

the liquid metal is held at 15 psig, and is only a fraction of a psi below the gas pressure in the bubbler line. In order to prevent gas loss from the liquid metal, it is held at the fill temperature and under elevated argon pressure until the time when system fill takes place.

D. Procedure for Liquid Fill Runs

A typical all liquid fill run is performed as follows: The reservoir contains a supply of high purity potassium adequate to fill the circuit. The upper valve on the reservoir is opened to allow pressure monitoring and to allow expansion of the potassium liquid, and the level of dissolved gas is set by the procedure described. The reservoir is then pressurized to 5 to 10 psig, the liquid in the reservoir is heated to the predetermined fill temperature, and the preheater-boiler unit is preheated to the same temperature. The circuit is then evacuated to establish the residual inert gas pressure level. The system is now ready for the fill process. The valve on the bottom of the reservoir is opened slowly to fill the flow circuit with potassium. The saturation temperature is controlled by the argon pressure above the liquid in the reservoir, since the valve remains open. The potassium is circulated at a fixed flow rate while power is applied to the preheater and boiler to increase the temperature very gradually. Continuous recordings are maintained on supply tank pressure, several boiler temperatures, and potassium flow. The boiler temperature continues to rise until boiling inception is encountered. The boiler power is increased above this point until reasonably steady boiling occurs for a period of time long enough to ensure thermal equilibrium. The power is then decreased until boiling ceases, the power again increased to bring

about boiling, maintained above boiling and decreased. This procedure is usually repeated several times to observe the reproducibility of the boiling inception temperature. Records of electrical power, condenser water temperature rise and flow rate, thermal flowmeter conditions and other data not continuously recorded are made during thermal equilibrium.

The flow rate may then be changed while the reservoir pressure is held constant, and the temperature raised to bring about boiling, and again repeated. In some runs, tests were made at several flow rates and several saturation temperatures. At the termination of the run the reservoir valve is closed and the system is drained and pressurized with argon to prevent contamination.

E. Procedure for Two-Phase Fill Runs

A typical two-phase fill run is performed as follows: The reservoir contains a supply of high purity potassium adequate to fill the circuit. The upper valve on the reservoir is opened to allow pressure control and to allow expansion of the potassium liquid. The level of dissolved gas is then set by the procedure previously described, the reservoir is pressurized to 5 to 10 psig, and the liquid in the reservoir is brought to the appropriate fill temperature. The preheater-boiler unit and coupling tubing is preheated to the fill temperature, and evacuated to establish the residual inert gas pressure level.

The system is now ready for the fill process. Potassium is introduced to bring the liquid to a given level by opening the valve at the bottom of the reservoir a very small amount, so that the potassium flows out slowly

and rises in both the preheater and in the thermal flowmeter. After the liquid has reached a predetermined level, determined by the liquid level measuring system, the valve is closed at the bottom of the reservoir, so that an argon- and vapor-filled space exists above the potassium in the boiler and condenser.

The electromagnetic pump current is increased to a value which maintains a small pressure head between the boiler and condenser. The system is now in a condition to boil at reduced pressure, since the condenser temperature is regulated by the cooling water temperature of 180°F and the boiler is at the fill temperature many hundreds of degrees higher. In some runs with low initial inert gas pressure, alternate superheating and violent phase change occur immediately after fill. In others, with higher inert gas pressure and lower fill temperature, the liquid metal temperature is below the saturation temperature corresponding to the existing pressure level so that boiling inception does not occur until the temperature is raised. Under the circumstances described, the mass flow rate around the circuit is determined by the equality between the two-phase pressure drop and the difference in saturation temperature between the boiler and condenser. Therefore, if reasonably steady nucleation occurs, the flow rate is acceptably steady. If, on the other hand, the liquid superheat temperature is very large, and periods of several seconds elapse between explosive changes in phase, no steady flow is established at all, even with the circuit flow damping valve closed almost completely.

For cases in which steady nucleation occurs, small step increases in the power level increase the liquid mass flow and the saturation temperature

together, and small step increases in the electromagnetic pump current maintain the liquid level in the boiler. These increases are made until the saturation temperature has reached a predetermined maximum level. The saturation temperature, therefore, sweeps through all of the temperatures between the fill temperature and the test maximum. When the system is in acceptably steady boiling, records of power input, condenser heat flow, and other data not continuously recorded are made.

After the complete range of saturation temperatures has been covered, the power level is reduced and usually the entire process is repeated to test boiling inception without refill, as has been the procedure with the all-liquid-fill tests. At the termination of the runs, the liquid metal is drained from the potassium circuit and discarded.

Several two-phase runs have been combined with all-liquid fill runs in the following manner. After the completion of the two phase fill experiments associated with a particular fill process, the supply reservoir is opened to fill the system completely and the pressure set to provide a particular saturation temperature. The system is then taken through an all-liquid fill start-up process, but with the same fill liquid, inert gas level, etc., as the preceding two-phase fill run. Therefore, a direct comparison of results for the two types of start-up operation can be made. The point may be made that the additional liquid from the supply reservoir changes the conditions in the system. However, the system is typically 90 percent full during a two-phase fill run so that the additional liquid required to fill the system is a small portion of the total and, in addition, has the same dissolved inert gas level and fill temperature as the liquid introduced into the system at the beginning of the run.

IV. EXPERIMENTAL RESULTS

A total of eighteen separate fill and start-up sequences were involved in the program. Eight of these were all-liquid-fill start-up processes, and ten two-phase. All-liquid-fill data were also taken at the termination of four of the two-phase fill runs by filling the system completely and controlling the saturation pressure through the inert gas pressure level at the reservoir. The procedures for obtaining these latter data correspond exactly to those procedures used in the liquid fill runs, except the fluid has the same history as that in the corresponding two-phase fill procedure.

The principal experimental data are presented in Tables IV-I and IV-II. Table IV-I contains all-liquid-fill results not only from the all-liquid-fill start-up processes, but from the all-liquid-fill terminations of the two-phase start-up runs, while Table IV-II contains only two-phase fill data. Both incipient and nucleate boiling superheat data are presented.

The nucleate boiling data presented in the tables have been selected from many hours of continuous records taken during the runs, and care has been taken that the operating conditions were maintained for a sufficient length of time so that thermal and hydrodynamic equilibrium was established. The lack of steady conditions eliminates much of the potentially useful data accumulated, since the processes involved in liquid superheat are not only by their nature unsteady, but they tend to be violent. A discussion of these data is contained in Section V. C.

TABLE IV-I.
POTASSIUM LIQUID SUPERHEAT DATA
ALL-LIQUID-FILL START-UP

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure Before Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F
NUCLEATE BOILING DATA							
1-28-71	16:55	830	0.10	D	3.2	1380	80
2-26-71	16:30	810	0.090	D	2.0	1360	80
2-26-71	16:55	810	0.090	D	2.0	1360	80
3-17-71	16:18	780	0.095	D	3.4	1420	80
3-17-71	16:39	780	0.095	D	3.4	1420	80
4-29-71	15:01	815	0.11	D	0.6	1415	26
4-29-71	15:16	815	0.11	D	0.6	1415	43
4-21-71	16:00	890	0.004	D	3.1	1340	95
4-21-71	16:06	890	0.004	D	3.1	1340	69
4-21-71	16:17	890	0.004	D	3.1	1340	78
4-21-71	16:22	890	0.004	D	3.1	1340	78
4-16-71	16:44	860	0.095	S	3.2	1335	87
4-16-71	16:57	865	0.095	S	3.2	1335	61
ADDITIONAL ALL-LIQUID-FILL DATA FROM TWO-PHASE START-UPS (SEE TEXT)							
9-22-71	15:33	1104	0.05	D	1.45	1303	17
9-22-71	15:37	1104	0.05	D	0.91	1295	17

TABLE IV-I. (Continued)

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure Before Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F
9-22-71	15:41	1104	0.05	D	1.09	1320	44
9-8-71	15:05	800	0.12	S	2.18	1278	8
9-14-71	15:42	846	0.04	S	1.38	1468	17
INCIPIENT BOILING DATA							
1-28-71	16:44	830	0.10	D	3.2	1380	160 First Initiation
2-26-71	16:27	810	0.090	D	2.0	1360	110 First Initiation
2-26-71	16:50	810	0.090	D	2.0	1360	100
3-17-71	16:13	780	0.095	D	3.4	1420	120 First Initiation
3-17-71	16:34	780	0.095	D	3.4	1420	95
4-29-71	14:56	815	0.11	D	0.6	1415	87 First Initiation
4-29-71	15:11	815	0.11	D	0.6	1415	147
4-29-71	15:19	815	0.11	D	0.6	1415	204
4-29-71	15:32	815	0.11	D	0.6	1415	264
4-29-71	15:41	815	0.11	D	0.6	1415	217
4-21-71	15:55	890	0.004	D	3.1	1340	52
4-21-71	16:06	890	0.004	D	3.1	1340	78
4-21-71	16:17	890	0.004	D	3.1	1340	78
4-21-71	16:22	890	0.004	D	3.1	1340	61

TABLE IV-I. (Continued)

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure Before Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F
4-16-71	16:39	865	0.095	S	3.2	1335	43 First Initiation
4-16-71	16:52	865	0.095	S	3.2	1335	43

ADDITIONAL ALL-LIQUID-FILL DATA FROM TWO-PHASE START-UPS (SEE TEXT)

46	7-27-71	15:55	800	0.31	D	0	1286	261
	9-8-71	15:05	800	0.12	S	2.18	1278	43
	9-14-71	15:22	846	0.04	S	1.38	1261	176
	9-14-71	15:31	846	0.04	S	1.24	1381	251
	9-14-71	15:42	846	0.04	S	1.38	1468	204

TABLE IV-II.
POTASSIUM LIQUID SUPERHEAT DATA:
TWO-PHASE FILL START-UP

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure After Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F	
NUCLEATE BOILING DATA								
47	7-27-71	15:24	800	.31	D	0	1481	13
	8-3-71	15:12	800	.032	D	4.18	1200	43
	8-3-71	15:25	800	.032	D	1.82	1372	65
	8-18-71	14:24	800	.050	D	1.27	1116	161
	8-18-71	14:27	800	.050	D	1.27	1099	161
	8-18-71	14:43	800	.050	D	1.27	1209	173
	8-18-71	15:05	800	.050	D	1.82	1209	121
	8-18-71	14:06	800	.050	D	1.09	998	50
	8-18-71	14:57	800	.050	D	1.46	1372	105
	8-25-71	14:45	800	.040	D	1.82	1459	53
	8-25-71	14:48	800	.040	D	1.09	1485	53
	8-25-71	16:11	800	.040	D	1.09	1330	68
	8-25-71	16:15	800	.040	D	1.09	1372	70
	8-25-71	16:25	800	.040	D	1.09	1433	70
	9-2-71	15:53	824	36μ	D	2.72	1200	108

TABLE IV-II. (Continued)

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure After Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F
9-2-71	15:24	824	36 μ	D	0.91	1222	108
9-8-71	14:37	800	.12	S	3.27	1158	86
9-8-71	14:16	800	.12	S	3.64	1243	86
9-14-71	14:40	846	.040	S	2.18	1244	86
9-14-71	14:59	846	.040	S	2.00	1244	86
9-14-71	14:46	846	.040	S	1.82	1205	146
9-22-71	14:39	1104	.050	D	2.36	1150	68
9-22-71	14:40	1104	.050	D	2.55	1162	64
48 9-22-71	14:43	1104	.050	D	2.10	1162	120
9-22-71	14:45	1104	.050	D	1.84	1158	112
9-22-71	14:48	1104	.050	D	2.10	1183	147
9-22-71	15:01	1104	.050	D	1.85	1244	180
9-22-71	15:10	1104	.050	D	1.27	1485	162
9-22-71	15:14	1104	.050	D	1.45	1547	153
9-22-71	15:17	1104	.050	D	1.45	1556	154
INCIPIENT BOILING DATA							
9-2-71	14:22	824	36 μ	D	0	1070	260 First Initiation
8-25-71	14:24	800	.04	D	0	947	169 First Initiation

TABLE IV-II. (Continued)

Date	Time	Fill Liquid Temp, °F	Inert Gas Pressure After Fill psia	Dissolved Gas in Potassium D - Degassed S - Saturated	Liquid Velocity in Test Section, feet/second	Saturation Temperature °F	Liquid Superheat °F
7-21-71	16:25	848	30.0	D	0	1415	110
8-3-71	14:42	800	.032	D	0	947	279 First Initiation
7-27-71	14:53	800	.31	D	0	1040	173 First Initiation
8-3-71	15:12	800	.032	D	4.18	1200	60

V. INTERPRETATION OF RESULTS AND DISCUSSION

A. Nucleate Boiling and Liquid Superheat Phenomena

1. Literature Survey

a. Nucleation Concepts

The high heat fluxes found in nucleate boiling are attributed to contributions of 1) transient conduction to, and subsequent replacement of, superheated liquid layer in contact with the heating surface; 2) evaporation of the liquid microlayer at the base of a growing bubble; and 3) transport of liquid in the vicinity of a growing bubble, due to thermo-capillarity effects on the vapor-liquid bubble interface. Pertinent information on the important parameters that control nucleation is summarized below.

Superheat

The classical Nukiyama curve for boiling heat transfer from a heated surface is shown in Figure V-1. In this figure, ΔT_s is the difference between equilibrium wall temperature and the saturation temperature.

To initiate boiling, it is necessary to heat the liquid locally to a temperature $T_{inc} > T_s$. The quantity, $T_{inc} - T_s = \Delta T_{inc}$, is the superheat required for incipient nucleation at a given pressure p . In practical systems, ΔT_{inc} is normally measured

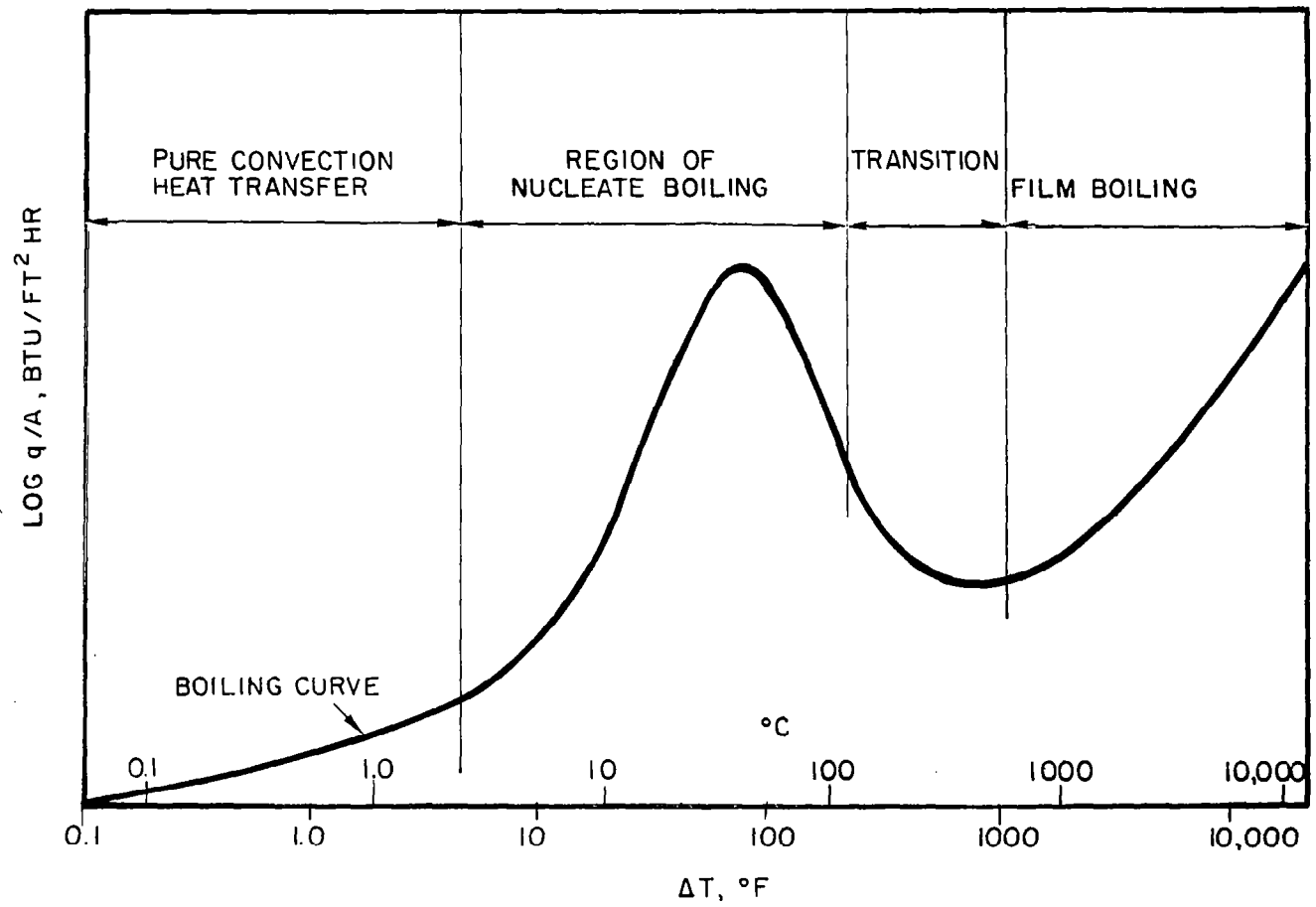


Figure V-1. Physical interpretation of boiling curve.

as $T_w - T_s$ where T_w is the wall temperature of the nucleation surface. Pertinent theoretical as well as experimental investigations reported in the literature more recently are given in the list of references.^{3 to 13, 21 to 26} When reviewing these references, one finds that the wall temperatures are measured at different points which do not always yield values relating to the nucleation sites. It is believed that this may be one of the reasons that nucleate boiling data are not always consistent. For example, thermocouple grooves may provide efficient nucleation sites and result in low superheats. After boiling starts, the wall temperature level is usually reduced to a lower equilibrium value. For example, in the case of boiling sodium, the incipient superheat has been measured to be 135°F and the subsequent equilibrium measured at 33°F. There is also information to indicate that ΔT_{inc} decreases with the forced flow rate (see Figure V-2).

Bubble Initiation

It is believed that the nucleation of vapor bubbles requires the presence of some vapor or gas volume in contact with the liquid to be vaporized. Otherwise, an infinitely large vapor pressure would be required to overcome surface tension in a vanishingly small spherical bubble in the liquid as can be seen from the classical force balance,

$$p_b = p_l + \frac{2\sigma}{r} = p_g + p_v \quad (V-1)$$

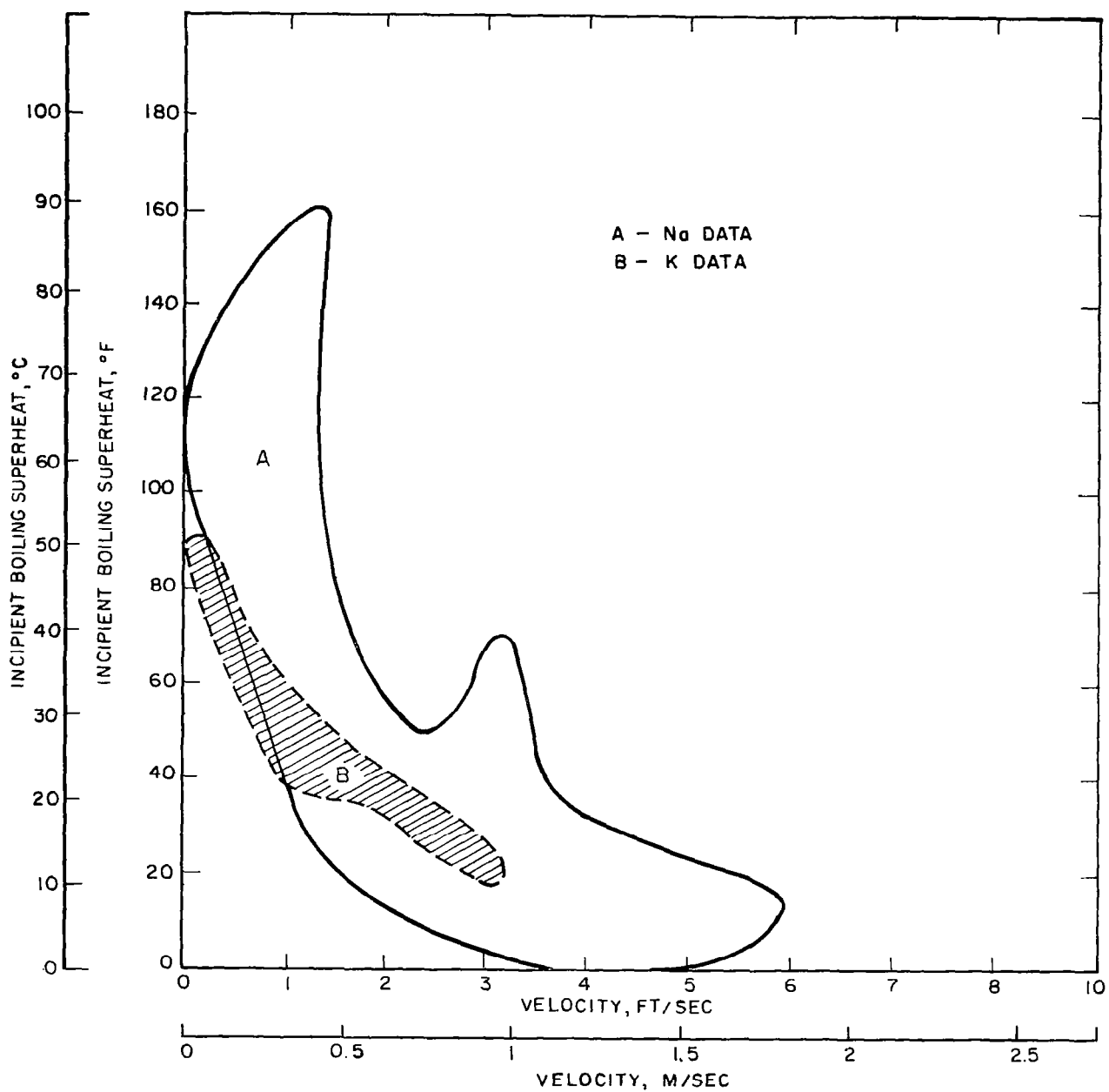


Figure V-2. Effect of flow rate on superheat, ΔT_{inc} (Ref. 1)

where

p_b , pressure inside bubble

p_g , inert gas pressure

p_ℓ , local pressure in liquid

p_v , vapor pressure

r , bubble radius

σ , surface tension

or

$$p_v - p_\ell = \frac{2\sigma}{r} - p_g \quad (V-2)$$

Equation (V-2) indicates that a smaller vapor pressure would be required to cause incipient nucleation if the gas content in the liquid was increased. When the wall (or vapor) temperature is above the saturation temperature, bubble growth would not proceed if the liquid into which the bubble grows was below the saturation temperature.

Bubble Growth from Cavities

Bubble growth from a solid surface depends on a variety of factors such as heat diffusion, system pressure, liquid superheat, cavity size, etc. A solid surface can contain many cavities of different shapes and sizes. These cavities may be wetted or nonwetted by the liquid that boils at the surface. Three simplified cavity shapes are discussed below.

If the surrounding liquid is subcooled and does not wet the surface, the shape of the vapor-liquid interface, which is in thermal and mechanical equilibrium with the surroundings, is as shown in Figure V-3. If the pressure of a stationary liquid system, which is at a uniform temperature, is suddenly reduced, the vapor-liquid interface will change to one of the possible nonequilibrium shapes and positions shown in Figure V-4. As the bubble forms a hemisphere at the cavity mouth, the vapor-liquid interface passes through a minimum radius of curvature R^* equal to the radius of the cylinder. At this stage, the pressure inside the bubble is

$$p_v = p_\ell + \frac{2\sigma}{R^*} \quad (V-3)$$

and the vapor temperature T_v^* is the saturation temperature corresponding to p_v . If the liquid temperature T_ℓ is exactly equal to T_v^* the bubble will not grow. Growth requires that $T_\ell > T_v^*$. It is conceivable for a bubble to reach the hemispherical shape even though $T_\ell < T_v^*$ due to inertia effects, provided the initial acceleration (and resulting momentum) is high enough. Generally, the effects of inertia are negligible during growth to the hemispherical shape, except in the very early stages.

Analytical results show that bubble growth to a hemispherical stage at the cavity mouth is completed in a few microseconds if the superheat is only 1°C above that required for equilibrium at the critical size; the precise time depending on cavity size and system pressure.⁴ Bubble growth calculations for the region

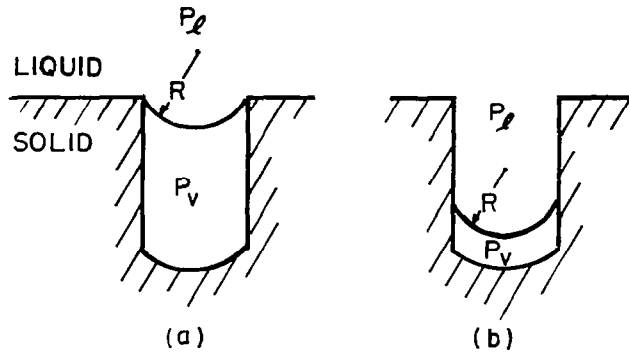


Figure V-3. Equilibrium shapes and positions of the interface (Ref. 4).

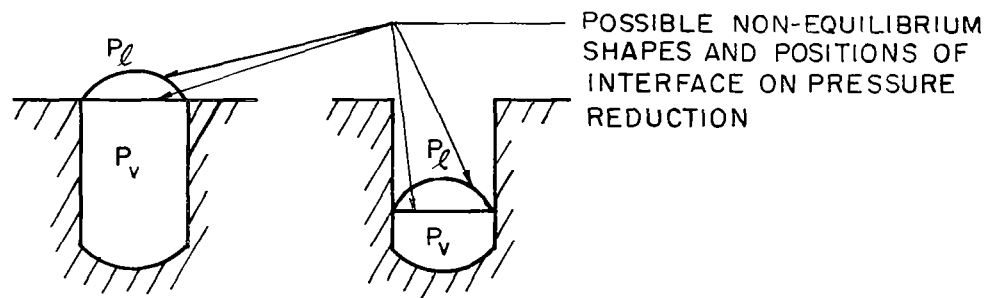


Figure V-4. Possible non-equilibrium shapes and positions of interface on pressure reduction.

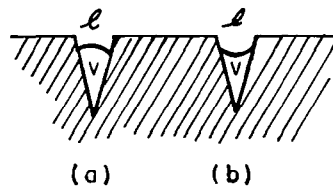


Figure V-5. Liquid-Vapor interface geometries in a conical cavity (Ref. 5).

well beyond the hemispherical stage show that bubble radius varies as the square root of time.

It is not necessary that inert gas be present for a bubble to grow in a conical cavity because some cavities can contain pure vapor even at very highly subcooled temperatures.^{5,6} Consider two cases of different contact angle β and corresponding concave and convex curvatures; in Figure V-5a, $p_v > p_\ell$, and in Figure V-5b, $p_v < p_\ell$. As the heat transfer surface cools below the saturation temperature of the liquid, the cavity in Figure V-5a, if it contained pure vapor, would collapse and completely fill with liquid, thus becoming inactive. As the cavity in Figure V-5b cools down, however, the interface recedes into the cavity, decreasing the radius of curvature and reducing p_v . Therefore, T_{sat} of the vapor decreases and the cavity does not completely fill with liquid and is ready as an active nucleus when the surface is subsequently heated.

The progress of liquid-vapor interface as it comes out of the cavity is shown in Figure V-6a, with cone angle ϕ and contact angle $\beta < 90^\circ$. In Figure V-6b, the magnitude of $1/r$, where r is radius of curvature, is plotted against the volume of vapor in the cavity. Note that at position b the interface radius of curvature is the radius of the cavity and $1/r$ is a maximum. This point is thought to correspond to a maximum required superheat for this cavity to nucleate.

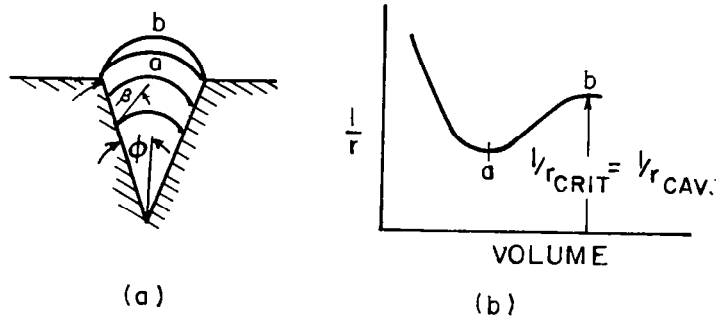


Figure V-6. Radius of curvature vs. vapor volume in a cavity (Ref. 5)

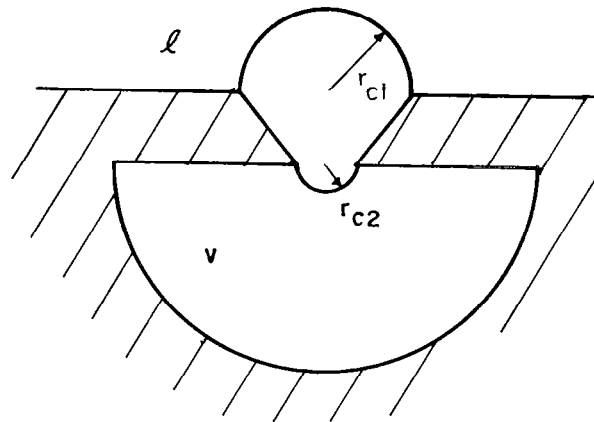


Figure V-7. Schematic view of a re-entrant cavity (Ref. 5)

If the cavity has neither sharp corners nor straight sides, the cavity radius is unidentifiable. Nevertheless, there exists an effective cavity radius which is identified with the superheat required for nucleation.

It was previously stated that, in the absence of an inert gas, cavities such as those shown in Figure V-5a and V-6a would become filled with liquid and become inactive upon being sub-cooled. A reentrant cavity, as shown in Figure V-7, could support some subcooling without filling the cavity with liquid.⁵ Here for $\beta = 90^\circ$, the critical radius determining the superheat required for nucleation is r_{c1} and the radius determining the amount of subcooling before liquid flows into the cavity is r_{c2} . The smaller the magnitude of r_{c2} , the larger the amount of subcooling the cavity can withstand. Sintered surfaces contain many such reentrant cavities. Ordinary machined metal surfaces probably contain such cavities also.

Effects of Surface Treatment

Since little data are available for liquid metals, results obtained for other liquids are presented to demonstrate some general characteristics.

The effect of past history on the nucleate boiling curve is vividly shown in Figure V-8. Note that for both surfaces, higher heat-transfer conductances are obtained when decreasing the heat flux after vigorous boiling. It is believed that additional cavity sites are activated at high heat fluxes by the spreading of boiling patches.

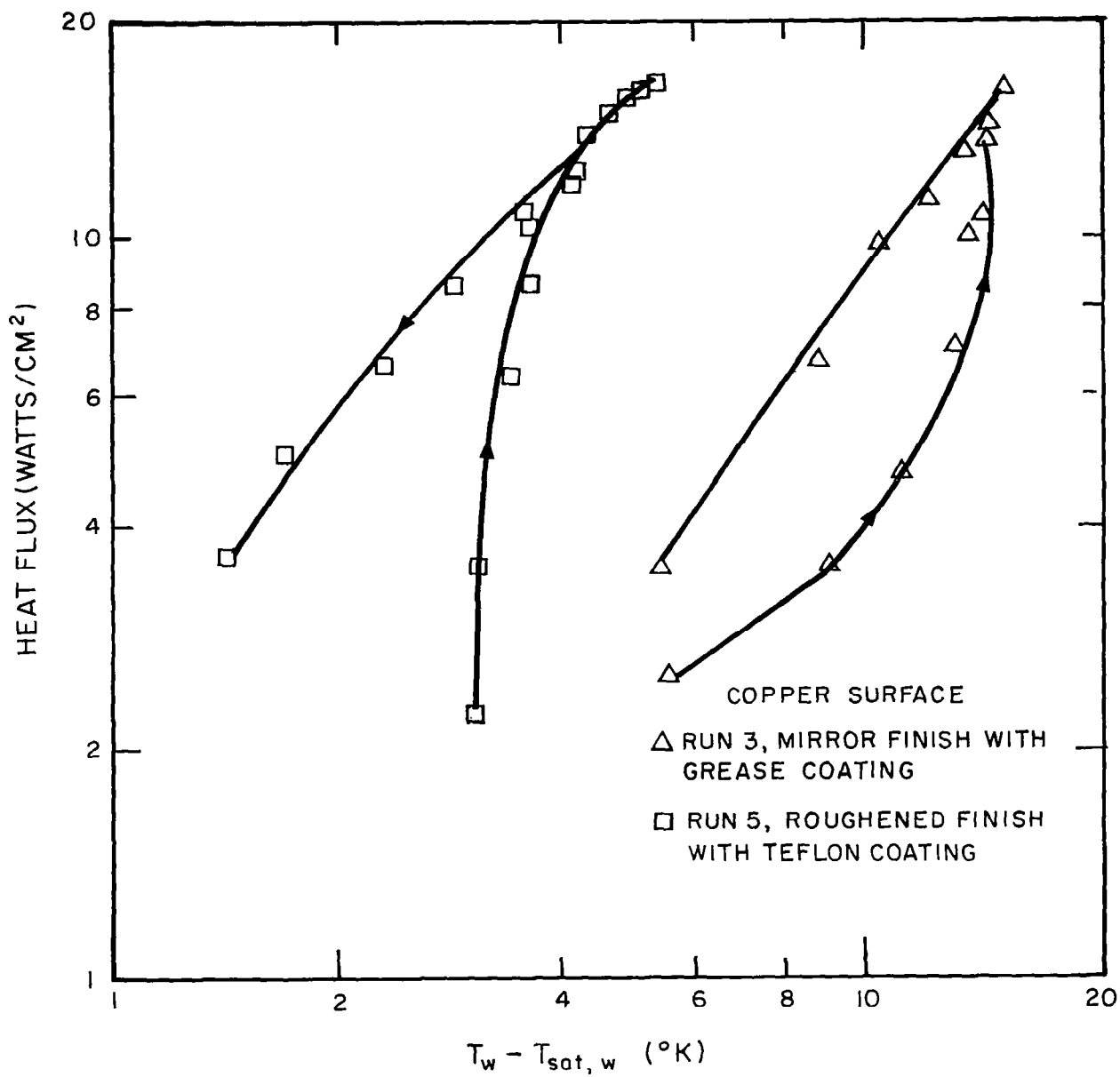


Figure V-8. Effect of past history on nucleate boiling curve for nitrogen (Ref. 7).

Upon decreasing power, some of these additional sites remain active with a corresponding increase in the heat-transfer coefficient.

The grease-coated surface showed a greater change in the boiling performance because, in addition to the aforementioned effect, the removal of grease around each active site during vigorous boiling decreased the amount of insulation produced by the grease.

Figure V-9 shows the individual coefficients of heat transfer measured for water boiling over copper plates having both smooth and rough surfaces.⁸ It is seen that the rougher surfaces give the higher coefficients. Figure V-10 shows the effect on Freon boiling when a brass wire screen, Mesh No. 80, is mounted on the boiling surface. It is seen that the screen improves boiling heat transfer at the lower ΔT region, but the effect vanishes at the higher ΔT 's.⁹ Similar boiling enhancement effects with screens were observed at Geoscience Ltd. However, other surface treatments proved more promising over a wider ΔT range, as shown in a subsequent section of this report.

The effect of the wall material on nucleate boiling is shown in Figure V-11, where the heat flux results obtained with a copper mirror finish are compared to those obtained with a nickel mirror finish. The observed results may be partially due to different microscopic surface conditions caused by a difference in hardness, even though both surfaces were polished in an identical manner.

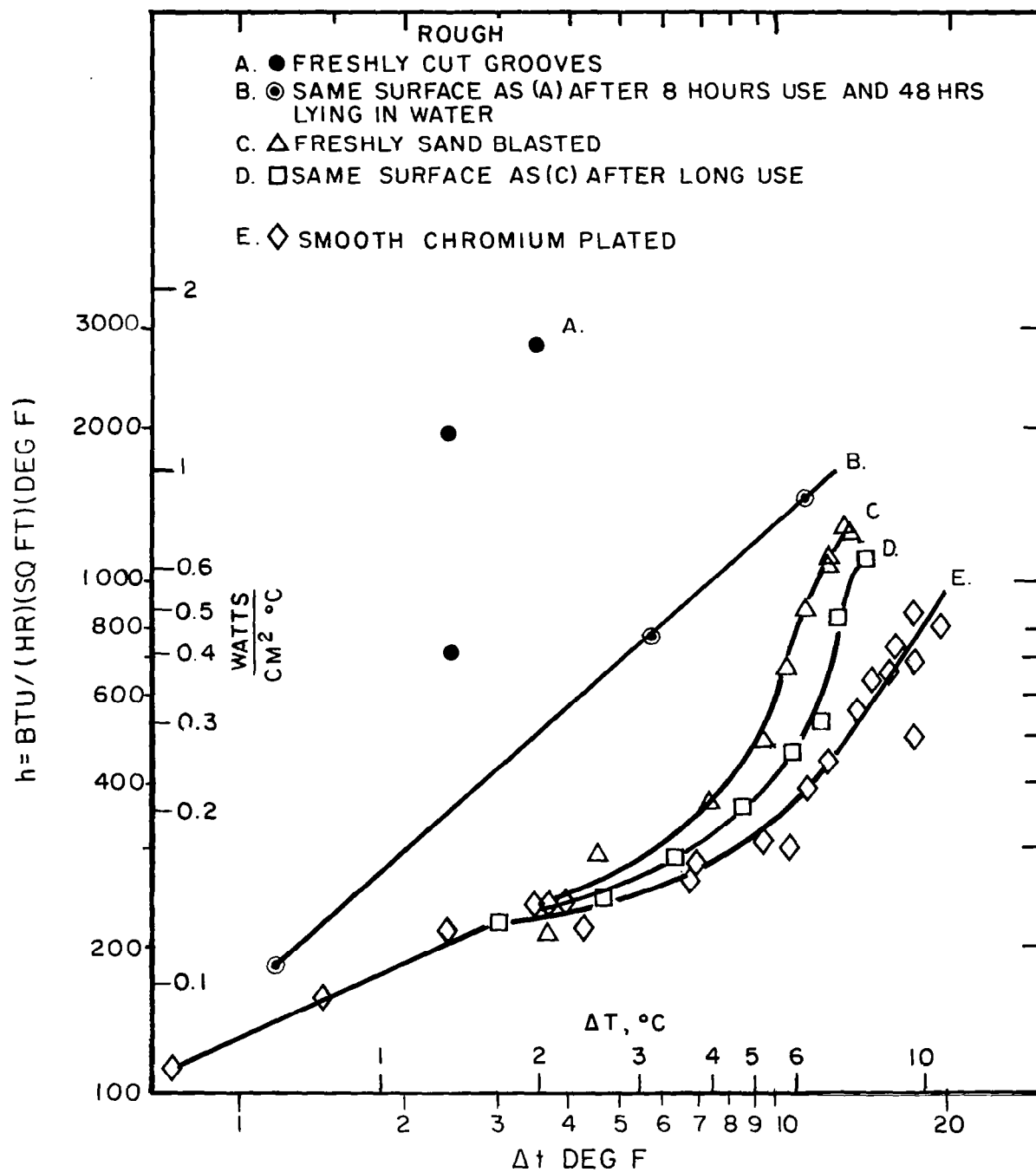


Figure V-9. Effects of surface conditions on heat transfer coefficient from horizontal plates to boiling water at 1 atm (Ref. 8).

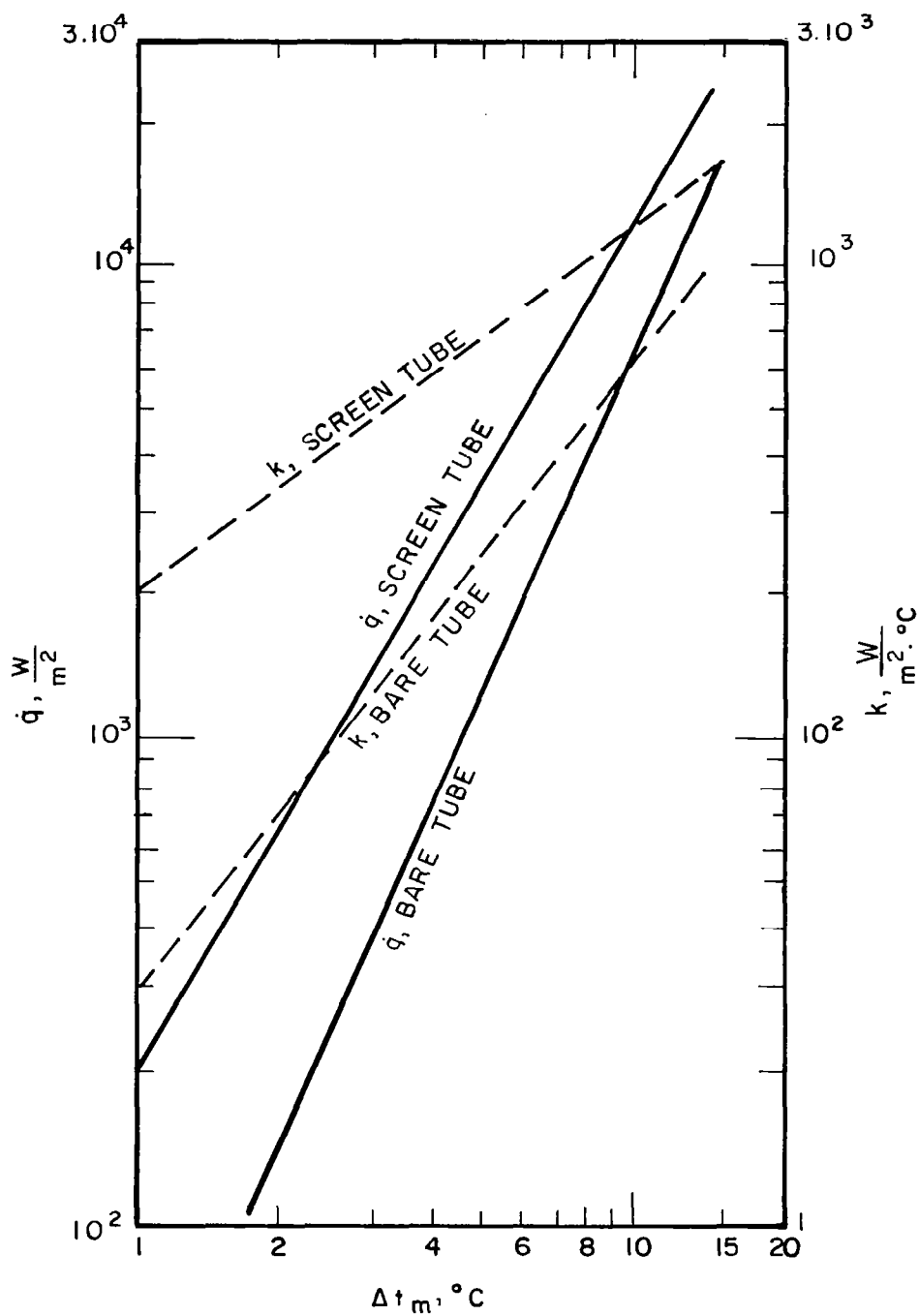


Figure V-10. Heat flux \dot{q} and overall heat transfer coefficient k versus Δt_m for Freon boiling inside a tube with and without a No. 80 mesh screen attached to the inside tube surface (Ref. 9).

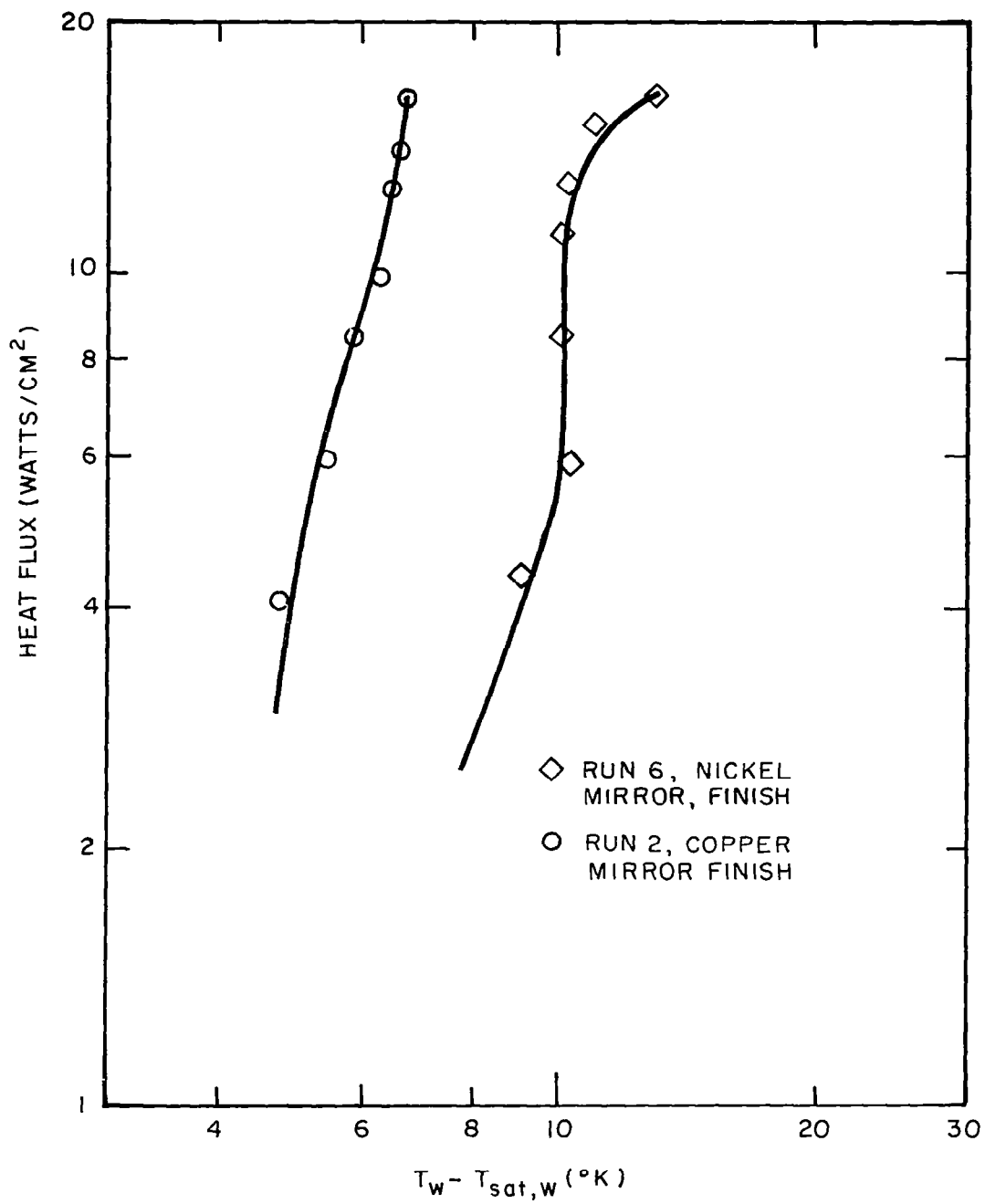


Figure V-11. Effect of materials on nucleate-boiling curve for nitrogen (Ref. 7).

Figure V-12 shows the effect of cavity size on the nucleate-boiling curve for nitrogen.⁷ By adding an artificial cavity to a mirror finish, boiling heat-transfer coefficients generally are increased. In addition, by increasing the cavity size, there appears to be a further improvement.

Figure V-13 represents data on incipient ΔT_{inc} measured for potassium with a boiler surface which had drill holes of 0.003-inch radius. It is seen that the measured superheats are generally higher than predicted for this drill hole radius. Typically, surfaces with artificial cavities are more likely to have potential nucleation sites than polished surfaces, as shown in Figure V-14.

From measured superheats, one can estimate the average bubble radius, Equation (V-3), which is a measure of the effective cavity size initiating nucleation. An example is shown in Figure V-15 for sodium. The experimental results appear to follow a line of constant radius for variable test fluid saturation temperatures. This seems to indicate that the same cavities are initiating nucleation regardless of the test fluid saturation temperature because the liquid bulk superheat and saturation temperatures result in constant bubble radius, Equation (V-3).

An important aspect of a potassium boiler is its behavior at the initial start up.¹⁴ Two-phase incipency results for a cavitating venturi, as a potassium boiler inlet device, is shown in Figure V-16. The minimum values of the throat pressure P_t obtained

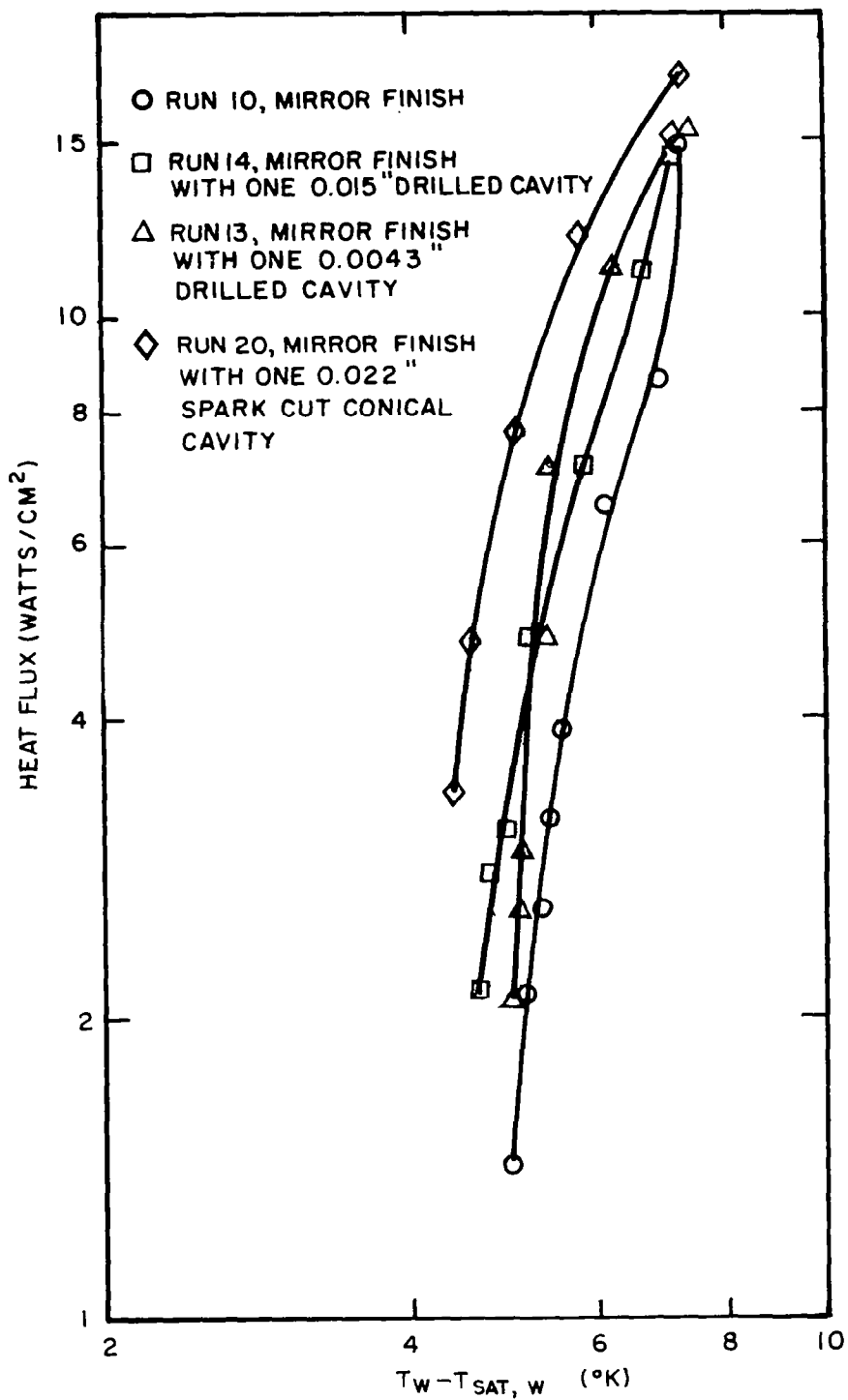


Figure V-12. Effect of the cavity size on nucleate-boiling curve for nitrogen (Ref. 7).

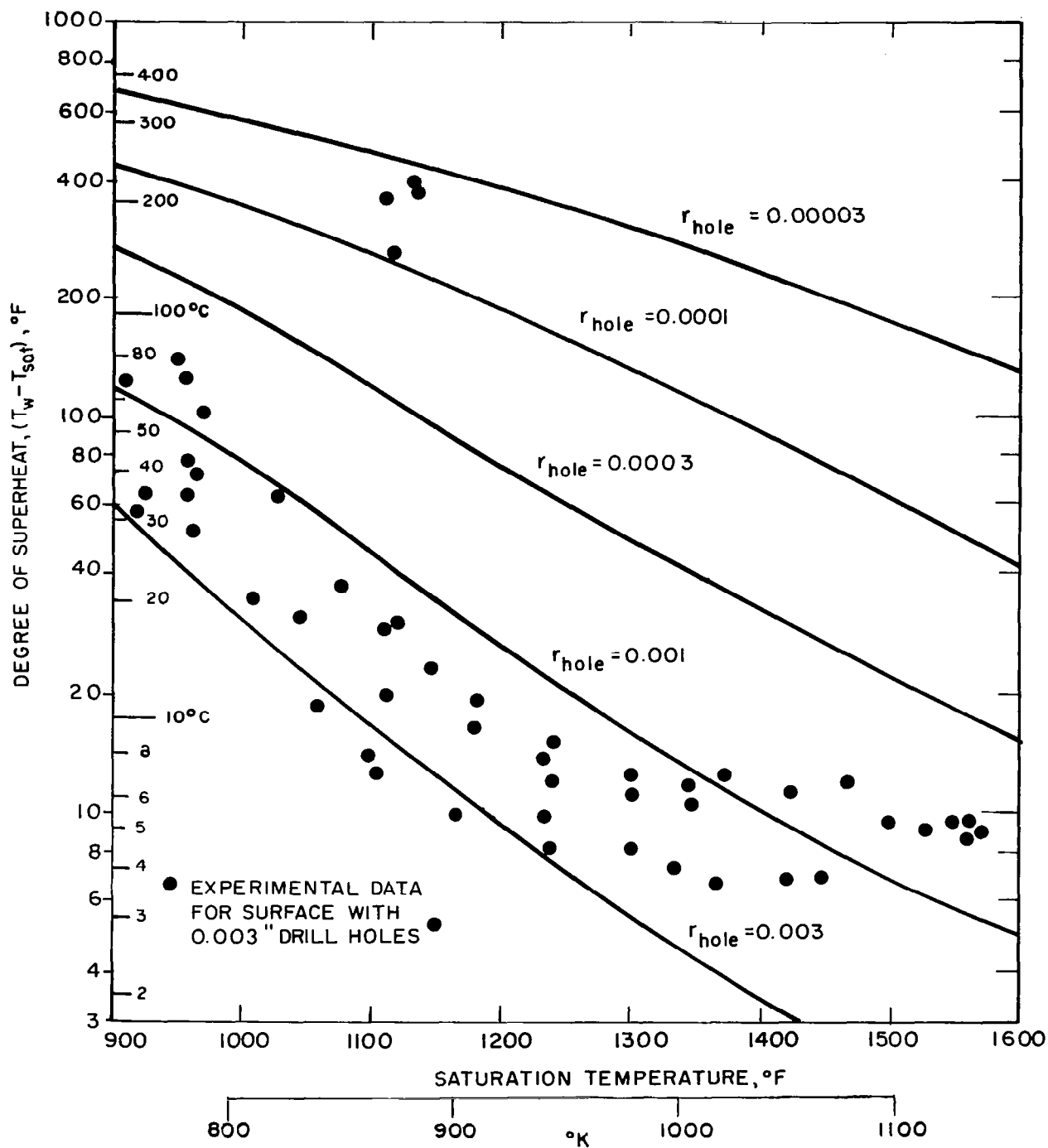


Figure V-13. Incipient boiling of K on surface with artificial drill holes of 0.003 inch radius (Ref. 3).

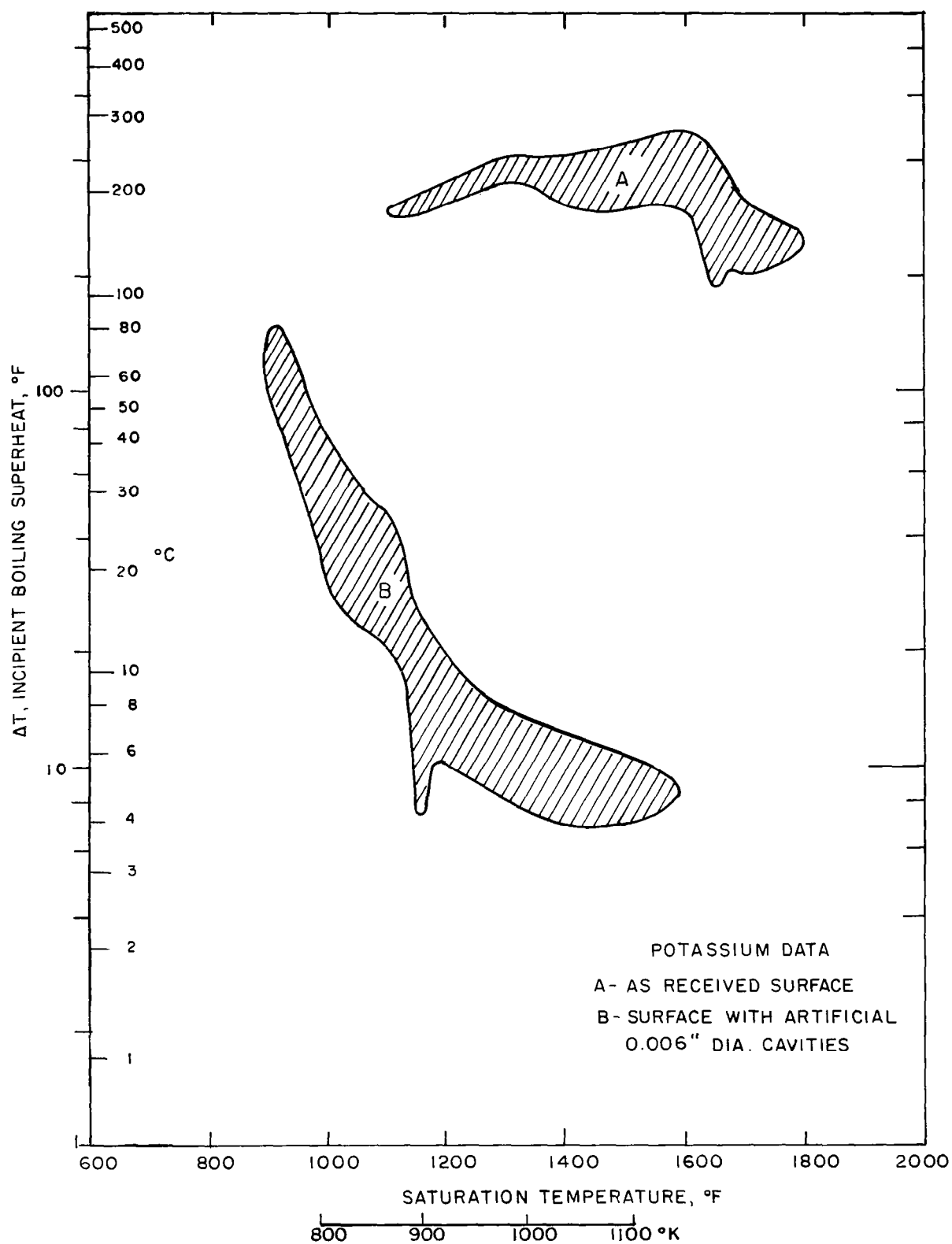


Figure V-14. Effect of surface roughness on superheat (Ref. 3).

TEST FLUID FLOWRATE, W_t

DATA OBTAINED BY

● 482 to 490 (60.7 to 61.7)
■ 228 (28.7)

RAISING HEATING FLUID INLET TEM-
PERATURE AT CONSTANT TEST FLUID
FLOW RATE AND EXIT PRESSURE

△ 487 (61.3)
◇ 313 to 320 (39.5 to 40.3)

LOWERING TEST FLUID EXIT PRESSURE
AT CONSTANT TEST FLUID FLOW RATE
AND HEATING FLUID INLET TEMPERATURE

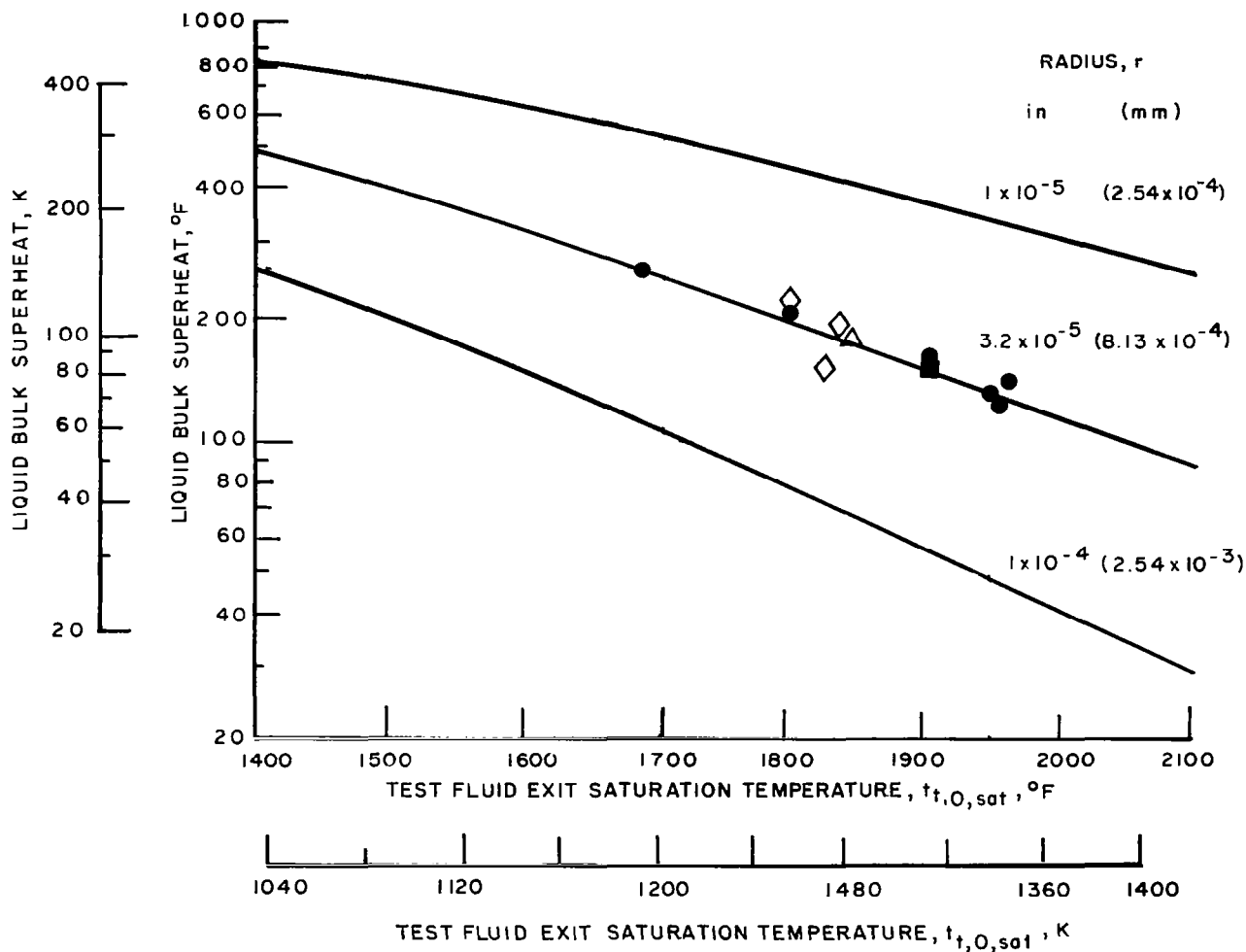


Figure V-15 Liquid bulk superheat required in sodium to initiate boiling at test fluid exit (Ref. 15).

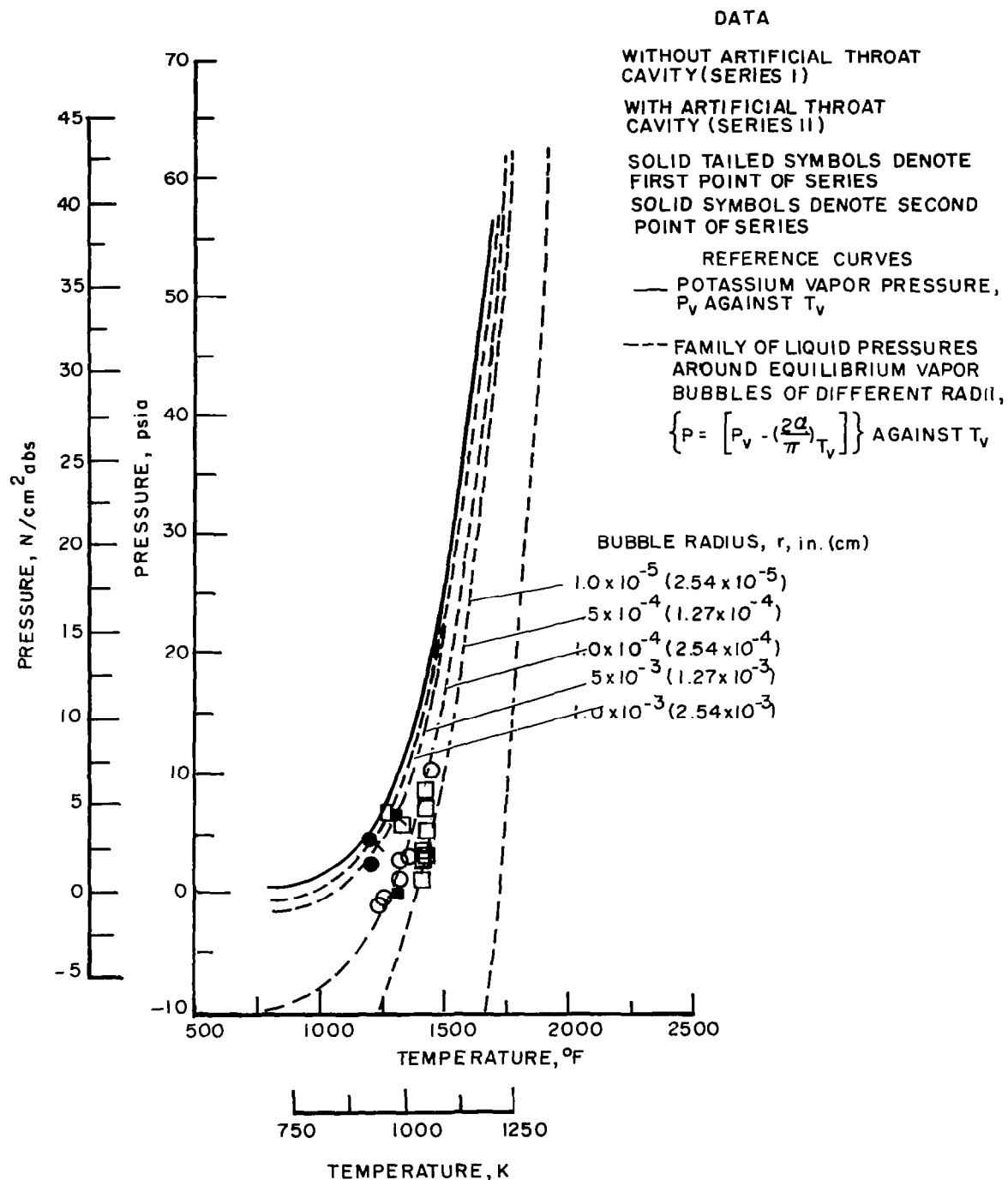


Figure V-16. Throat pressure as function of inlet temperature for incipient cavitation (Ref. 14).

before cavitation are shown as functions of liquid temperature. The results show data with and without an artificial throat cavity. The first cavitation point in each case occurred very closely to the potassium vapor pressure curve and did not follow the depression pattern of the rest of the cavitation incipency data. This difference appears to be caused by residual argon gas trapped in large size cavities, preventing them from flooding and thus making them active cavitation sites during the first pressure decrease. After the first cycle, most of the large sized cavities were depleted of gas and flooded to become inactive sites. In successive cycles the remaining smaller cavities caused larger decreases in liquid pressure to be necessary in order to trigger cavitation.

Figure V-17 shows the effect of the number of drilled cavities on the nucleate-boiling curve. The results show that an increase in the number of drilled cavities increases the boiling heat transfer. However, at high heat fluxes, the nucleate-boiling curves converge.

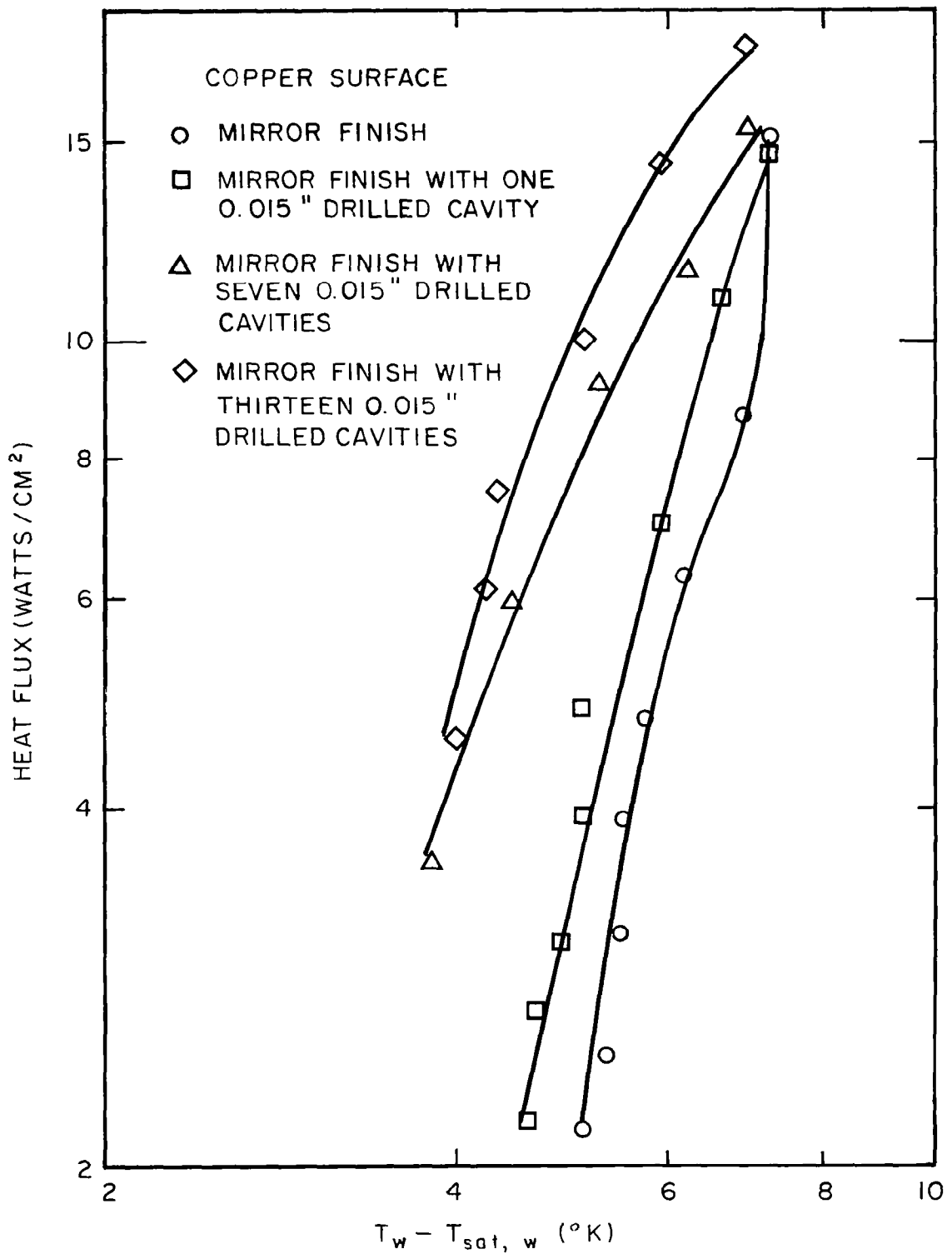


Figure V-17 Effect of number of drilled cavities on nucleate-boiling curve for nitrogen (Ref.7).

b. Nucleate Boiling Heat Transfer Mechanisms

It is clear that the lower the liquid superheat to initiate nucleation and the greater the nucleation site density, the greater will be the nucleate boiling heat flux. Therefore, the prime scope of this report deals with nucleation concepts (heat transfer, bubble initiation, bubble growth and treated surface effects). Although the scope of this program did not include the investigation of the nucleate boiling heat transfer mechanisms themselves, it is thought appropriate to at least summarize the important features involved.^{10,11,12,16,17}

There are two primary explanations for the high heat transfer fluxes observed in the nucleate boiling state. The most popular explanation has to do with bubble agitation. Specifically, it is felt that as vapor bubbles grow and collapse during their life, the superheated liquid in the boundary layer is stirred and, as a result, more heat is transported. This mechanical mechanism then is thought to reduce the convection thermal resistance in the boundary layer and improve the heat transfer. For further details, the reader might examine reference 11.

A second explanation of high heat fluxes in the nucleate boiling state (particularly under subcooled conditions) involves mass transfer from the bottom of the bubble (contiguous to the heating surface) to the top of the bubble. The effective heat transfer mechanism involved (vaporization from the bottom of the bubble and condensation at the top) in effect reduces the thermal resistances in the boundary layer.^{12,13}

A detailed numerical analysis under specific conditions has been carried out.¹² The results of the calculations indicate that it is possible to account for a large part of the heat transfer in nucleate, subcooled boiling in water by the mass transport through the bubble.

2. New Contributions and Interpretations

a. Surface Roughness Information

Some surface treatments improve boiling heat transfer without an increase of the number of cavities in the surface. Rather than providing more nucleation sites, such surface treatments result in improved heat transfer merely because the surface area is increased. A study was, therefore, made to determine the increase in surface area by several different types of treatments.

The microgeometry of a metal surface varies considerably for different types of surface finishes. Three basic idealized surface shapes can be identified (corresponding to the three finishing methods); see the representations shown in Figure V-18.

The orientations of these surface features may be directional or nondirectional, depending upon the finishing process. Milling, turning, and drilling result in a directional orientation while lapping, grinding, and electropolishing will result in a non-directional orientation of surface asperities.

The heights of the features were found to vary from ~ 0.02 microns for highly polished surfaces to ~ 250 microns for rough finishes.




<u>FINISHING PROCESS</u>	<u>SHAPE</u>
GRINDING	
BUFFING	
TURNING	

Figure V-18. Idealized surface geometries.

Table V-I^{16,17} lists the height of these surface asperities for the common finishing processes. The majority of these values were determined by the use of a profilometer.

Surface roughness can be defined in terms of a roughness factor, q ,

$$q = \frac{\text{actual surface area}}{\text{apparent surface area}} \quad (\text{V-4})$$

Roughness factors as high as 15 are reported for etched surfaces and as low as unity for electropolished surfaces.¹⁸ Table V-II lists the roughness factors for several metal surfaces and surface preparations. These values were obtained by adsorption or electrode capacity methods.

Little information on the width of surface asperities was found in the literature. The width or distance between roughness features would seem to depend on the rate of feed for the various finishing methods and on the abrasive particle size used. In order to obtain approximate values for the distance between surface irregularities, it was postulated that the surface projections were small regular four-sided pyramids of height, h . The length, a , of one side can then be shown to be

$$a = \frac{2h}{\sqrt{q^2 - 1}} \quad (\text{V-5})$$

TABLE V-I

HEIGHT OF SURFACE ASPERITIES FOR VARIOUS SURFACE FINISHES

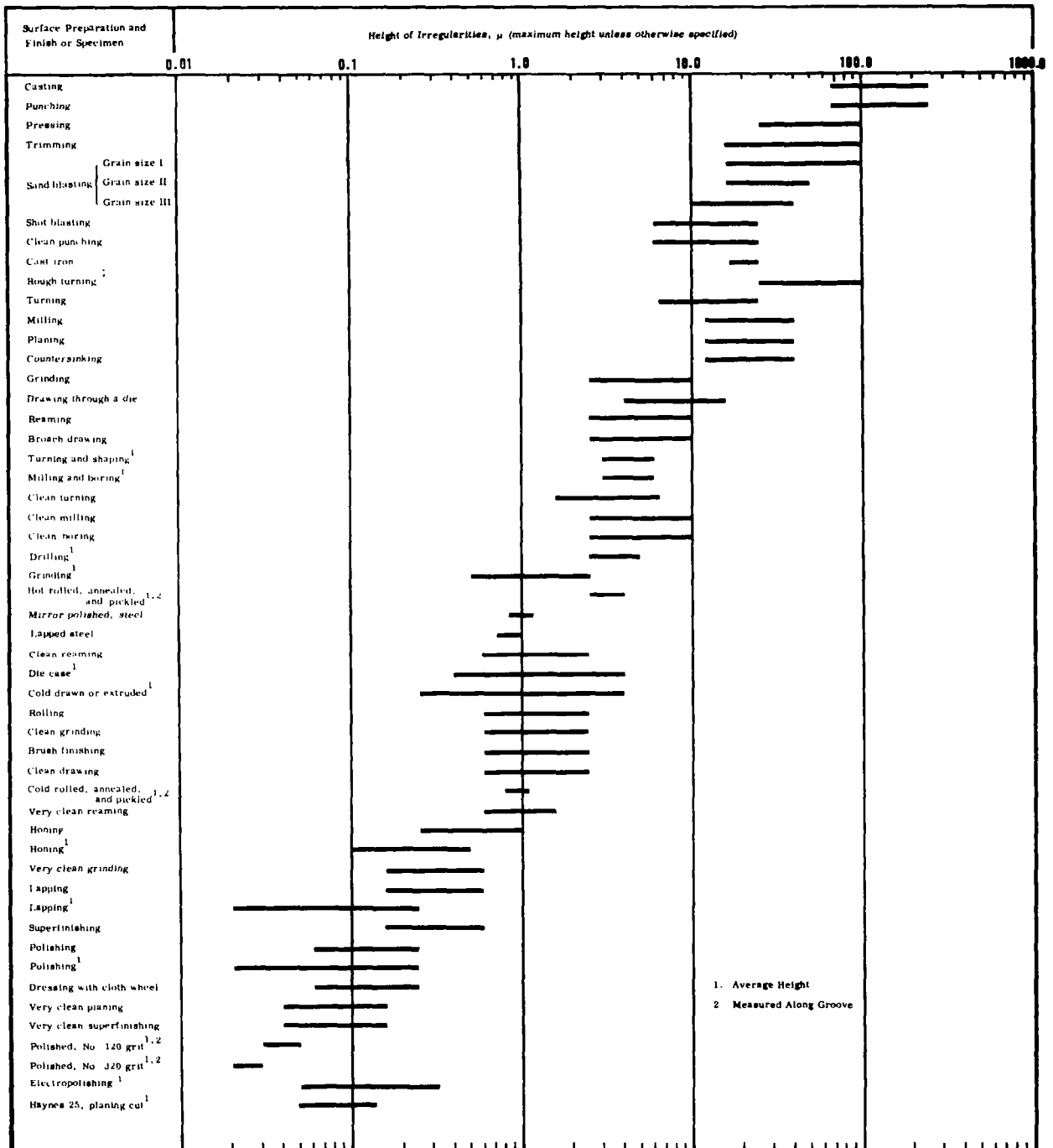


TABLE V-II.

ROUGHNESS FACTORS FOR VARIOUS METAL ALLOYS AND SURFACE TREATMENTS

Specimen	Surface Preparation	Roughness Factor
18-8 stainless steel	Pickled 25 vol. % HCl-25 vol. % H_2SO_4 , 35°, 10 minutes	4.12
18-8 stainless steel	Pickled 15 vol. % HNO_3 -10 vol. % HF, 90°, 10 minutes	1.36
18-8 stainless steel	Abraded 2/0 emery	3.06
Armco iron sheet	Abraded 2/0 emery	3.4
Armco iron sheet	H_2 reduced 1000°	1.25
18-8 stainless steel	Electropolished	1.12
Ag foil		5.
Ag	Etched	15.
Ag	Abraded	2.5
Cu	Electropolished	~1.0
Ni	Abraded	2.5
Ni	Polished	1.7
Ni foil		2.15

Using this equation, values for the distance between irregularities were calculated for several roughness factors, and h values obtained from Table V-I. Table V-III lists the calculated values of widths of surface irregularities for roughness factors of 2, 3, 4, and 15. For roughness factors of 2, 3, and 4, the width of the irregularities are of the same order of magnitude as their heights, and for a roughness factor as high as 15 the width is approximately one order of magnitude smaller than the height; the later case does not occur frequently in practice.

The grain sizes for niobium, niobium-zirconium alloy, and tantalum were also obtained from literature.⁷ Table V-IV lists the grain size of these metals and alloys for several specimens with different heat treatments; the values varied from 16 microns to approximately 350 microns. The smallest grain diameter of the metals studied was 16 microns. This value is much larger than the height or width of surface irregularities of many surface finishes. For example, for a highly polished surface, the grain size would be larger than the surface irregularities by a factor of 10^3 . Nevertheless, because etching is a selective process and dependent upon grain orientation, the surface irregularities caused by etching can vary and also be smaller than the grain sizes. Most potential cavities would, therefore, have effective diameters which are orders of magnitudes smaller than the grain sizes.

b. Nucleate Boiling Experiments

Treated Surfaces

Geoscience Ltd has previously performed long-term exposure

TABLE V-III. CALCULATED SPACING OF SURFACE ASPERITIES.

Surface Preparation and Finish	Maximum Width of Surface in μ				
	0.01	0.1	1.0	10.0	100.0
Grinding $r = 2$					
Mirror polished steel					
Lapped steel					
Lapping					
Polishing					
Grinding $r = 3$					
Mirror polished steel					
Lapped steel					
Lapping					
Polishing					
Grinding $r = 4$					
Mirror polished steel					
Lapped steel					
Lapping					
Polishing					
Grinding $r = 15$					
Mirror polished steel					
Lapped steel					
Lapping					
Polishing					

TABLE V-IV. GRAIN SIZES OF METALS AND ALLOYS.

Specimen and History	Average Grain Diameter in μ					
	0.01	0.1	1.0	10.0	100.0	1000.0
Columbium E-B-M, cold rolled 90%, recryst. 2 hrs. at 100°C in vac (5×10^{-5} mm Hg)					—	
Comml. arc cast 1/2 in. dia. recryst. rod processed to unspecified size, hydrogenated matl. annealed 7 hrs. at 650°C in dry H_2				X		
E-B-M cold rolled 95%, recryst 2 hrs. at 1260°C in vac (10^{-5} mm Hg)					X	
E-B-M, cold forged, rolled and swaged from 3 in. dia. to 3/8 in. dia. recryst 2 hrs. at 1050°C				X		
Arc-melted, skull cast, cold-swaged 50% recryst. 16 1/2 hrs at 1400°C.					—	
Columbium-1.25% Zirconium. Fully recryst. and heat treated 1 hr. at 1149°C 1205°C 1260°C				X X X		
Tantalum. P-M 3/10 in. dia. swaged bar, recryst 1 hr at 1700°C in vac.				X		
P-M 1/100 in. thick sheet, recryst. in vac.				—		
E-B-M 2 in. dia. ingot, cold rolled 75%. recryst 1 hr at 1200°C				—		
E-B-M cold rolled 75%, intermediate anneal at 1200°C 1 hr annealing at 1200°C 1300°C 1400°C 1425°C 1600°C 1700°C 1800°C				— — — — — — —	X — — X X —	

experiments for nucleate boiling in Freon 113 on a variety of treated boiler surfaces. These test sections were sandblasted, electroplated, electroetched, knurled, threaded, chemically etched, metalsprayed, blanketed with metal screens and glass-cloth. Boiling conductances were improved by a factor of two to five times better than those for the standard, untreated test section, when measured at the same superheat temperature. It is anticipated that some improvements would be obtained for liquid metals when using such surface treatments.* However, experimental research of this nature was not included in the work scope for this report.

Cavity Boiling Experiments

In order to better understand and visually observe nucleate boiling in a cavity, capillary tubes, sealed at the bottom, were partially filled with Freon from the top, leaving an airspace at the bottom. The top of the capillary tube opened into a larger diameter tube, as shown in Figure V-19. The liquid filled the lower portion of the large diameter tube and the upper portion of the capillary tube, as shown. The capillary tube was heated with warm water and boiling was observed to start at the liquid-gas interface in the small diameter tube. The following observations of the boiling

* For low Prandtl number fluids, the controlling thermal resistance is usually not in the boundary layer. Therefore, nucleate boiling would not yield large increases in heat transfer.

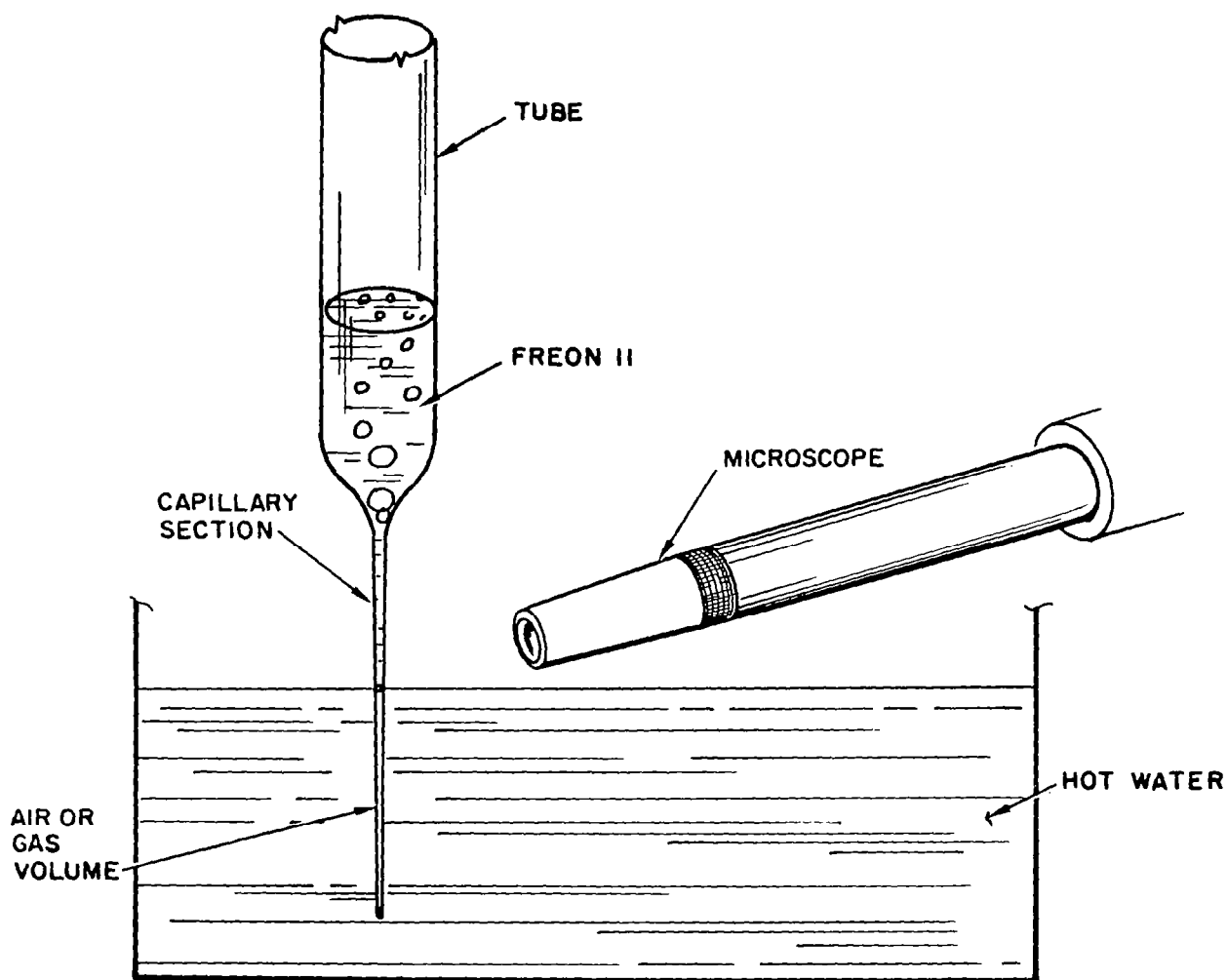


Figure V-19. Boiling experiments with Freon-11 in capillary tubes.

process were made with the aid of a microscope.

- (a) Boiling occurs at low superheat temperatures when liquid-vapor interface is heated.
- (b) When heating only the region around the gas-liquid interface in the small capillary tube, small bubbles rise in the center of the pipette and liquid flows back into the throat of the capillary section.
- (c) When liquid fills the capillary tube completely so that no gas volume is present, high superheat occurs and no boiling takes place below the high superheat temperatures.
- (d) Depending on the tube diameter, either (1) a slugging fill and boil pattern takes place, or (2) a continuous fill along the walls and boiling in the center takes place.
- (e) Once boiling is initiated, it continues as long as heat is added.

c. Hydrostatic Tension

The classical force balance described earlier in Equation (V-1),

$$p_b = p_\ell + \frac{2\sigma}{r}$$

indicates that for constant bubble pressure, p_b , the hydrostatic pressure, p_ℓ , is a function of the bubble radius. As the hydrostatic pressure is lowered, the bubble radius also decreases and

obtains a certain equilibrium value, r_o , for $p_l = 0$. If the liquid is brought into hydrostatic tension, p_l is negative, and the bubble radius obtain values below r_o . A typical example of this phenomena is illustrated in Figure V-20. If the liquid is perfectly degassed and all cavities with equivalent radii larger than r_o are inactivated, one would not expect nucleation with superheat because infinitely large vapor pressures would be required to overcome surface tension in a vanishingly-small spherical bubble in the liquid, Equation (V-1). However, nucleation does occur at somewhat higher initial superheats than what is required to maintain steady boiling. It is, therefore, thought that in any degassed system, incipient nucleation occur in microscopic cracks in the container which are smaller than r_o . As superheat is increased in the wall cavities, hydrostatic tension builds up inside the cavities until such values are reached that the bubble pressure is in equilibrium with Equation (V-1). At this point, incipient nucleation takes place. This theory would explain some of the unknown phenomena in nucleate boiling.

Hydrostatic tension in water has been measured to be as high as 280 bars before nucleation occurs.²⁰ It is, therefore, possible that nucleation can be initiated by cavities one or two orders of magnitude smaller than the equilibrium value, r_o , for $p_l = 0$, if the liquid in these cavities is brought into hydrodynamic tension by excessive superheat.

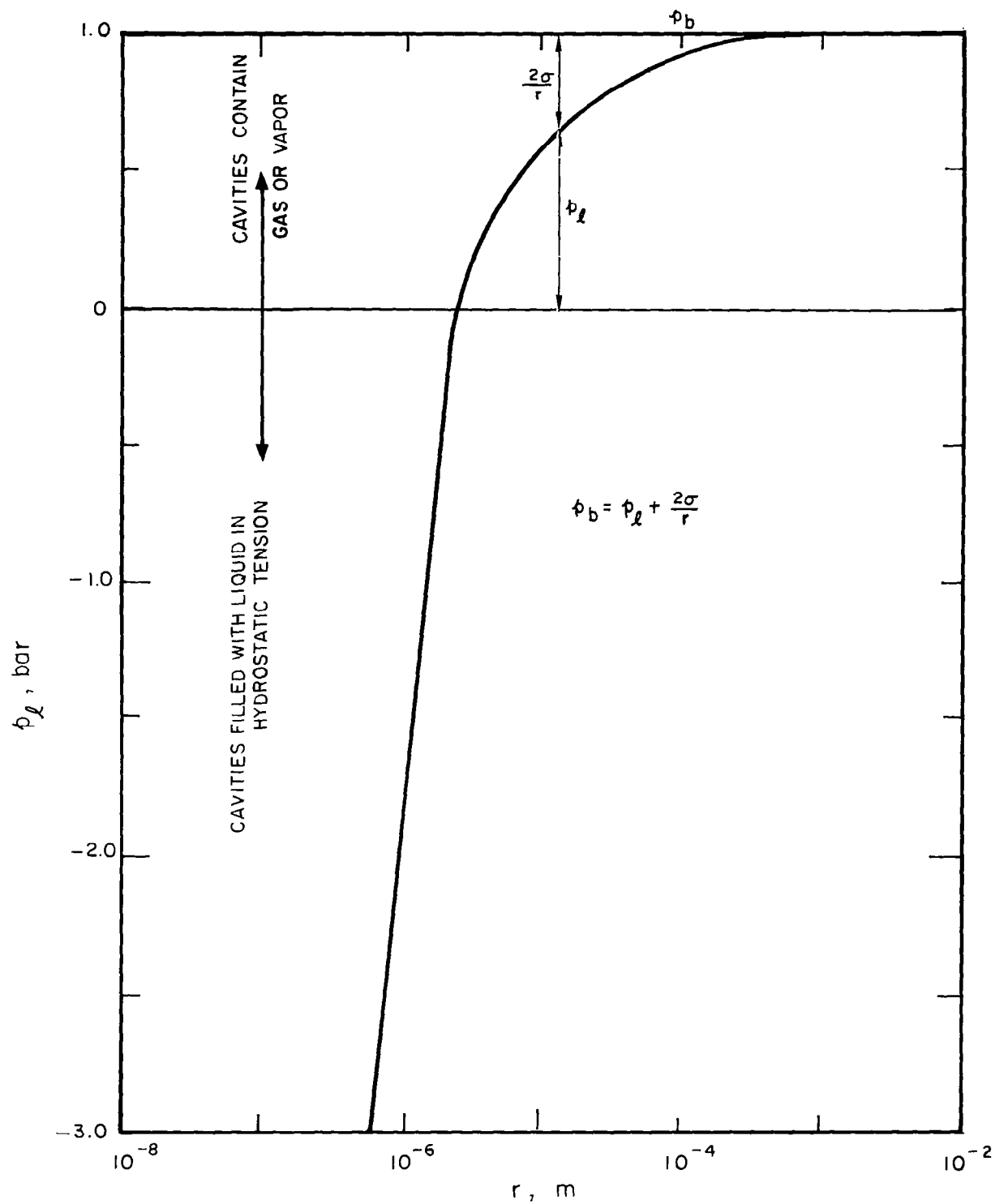


Figure V-20. Example of hydrostatic equilibrium in a bubble.

3. Discussion of Nucleate Boiling Factors and Contributions

On the basis of the studies conducted in this program, the following observations can be made.

Nucleation

- (a) In addition to the effects of surface roughness and the type of surface material, the presence of artificial cavities can reduce the wall superheat and improve nucleate-boiling heat-transfer coefficients.
- (b) The nucleate-boiling heat flux, in general, depends on the number of active sites.
- (c) In pool boiling at low heat addition, only a few cavities are active. As more heat is added, more cavities become active. It is thought that a few gas molecules are always present in microscopic cracks inside the cavities so that nucleate boiling can always be initiated. The bubble size and frequency, on the other hand, is a function of the cavity size and shape as well as the liquid and wall properties.
- (d) In nucleate-boiling, the presence of a thin layer of lubricating oil on the test surface can markedly decrease the boiling heat-transfer coefficient.
- (e) During the initial period of operation of a test section in nucleate-boiling, time variations in performance occur; similar behavior has been observed during start-up periods.

- (f) Controlled testing procedures are necessary to obtain reproducible nucleate-boiling data (because of the many variables involved).
- (g) Surface roughness alone will increase the surface area several times and this factor is believed to be a partial explanation for increased boiling heat transfer for many treated surfaces. On the other hand, increasing the number of cavities has also proven to increase nucleate boiling heat transfer.
- (h) Smooth surfaces retain a minimum of adsorbed gas and impurities; in turn, undesirable incipient superheat temperature could occur during start-up in liquid metal boiling systems. It may, therefore, be desirable to treat internal tube surfaces to obtain lower incipient superheat temperatures. This possibility is of particular interest in potassium Rankine cycle systems which are under high vacuum during the filling process (most cavities are pumped free of inert gases and only a few would be in an active stage for incipient nucleate boiling).

B. Models for Boiler Wall Temperature Transients

1. Wall Temperature Variations During Nucleation Transients

Usually the nucleate boiling heat transfer models found in the literature are defined on a steady state basis (i.e., mean wall temperatures are utilized). The heat transfer mechanisms involved are actually transient or periodic, however, with wall-liquid interface temperatures that are not constant or uniform. For example, prior to the initiation of a bubble, the heat transfer wall is at some maximum temperature. As the bubble originates and begins to grow, heat is transferred to the bubble from the surrounding liquid and the heat transfer wall. During this process of vaporization, superheat is removed from the liquid and the wall. After the bubble has been generated, one would expect the wall temperature underneath the bubble to have dropped to some minimum temperature. The local surface temperature of the wall then again increases in temperature as a result of heat conduction from the surrounding, warmer wall regions. This process must play a part in defining bubble size and the growth rate. Derivations have been made by Geoscience of transient temperature solutions for thin, flat plates that have sudden local changes in boiling characteristics (because of the initiation or termination of local boiling). It is believed that such models can be used to define bubble time constants and sizes. An example of such an analysis is presented in the following paragraphs.

Idealized System

It is postulated that nucleate boiling is taking place on a narrow band of

a boiler tube surrounded by non-boiling convection. The band is thought of as being one bubble wide, thereby simulating a one-dimensional bubble system. As a result of this non-uniform heat transfer conductance distribution, a wall temperature variation exists. Then, suddenly the boiling process terminates, the conductance distribution becomes uniform and the non-uniform temperature field in the boiler tube wall rises until it attains a new, uniform equilibrium value. From the solution of this boundary value problem, information on time constants and variations in local wall superheat can be deduced.

Derivation

Figure V-21 shows a sketch of the geometry and transient temperature field for the problem under consideration. The differential equation for this system (defined by convective heat transfer to and from the wall, lateral conduction along the thin wall, and heat storage) is

$$-\alpha \left(t - \frac{h_1 \tau_1 + h_2 \tau_2}{h_1 + h_2} \right) + \frac{\partial t^2}{\partial x^2} = \frac{1}{a} \frac{\partial t}{\partial \theta} \quad (\text{V-6})$$

where

- x , lateral distance along boiler tube element (normal to initial boiling band)
- t , boiler tube temperature
- h_1 , hot liquid convective conductance
- τ_1 , hot liquid temperature
- h_2 , saturated liquid convective conductance
- τ_2 , saturated liquid temperature
- θ , time

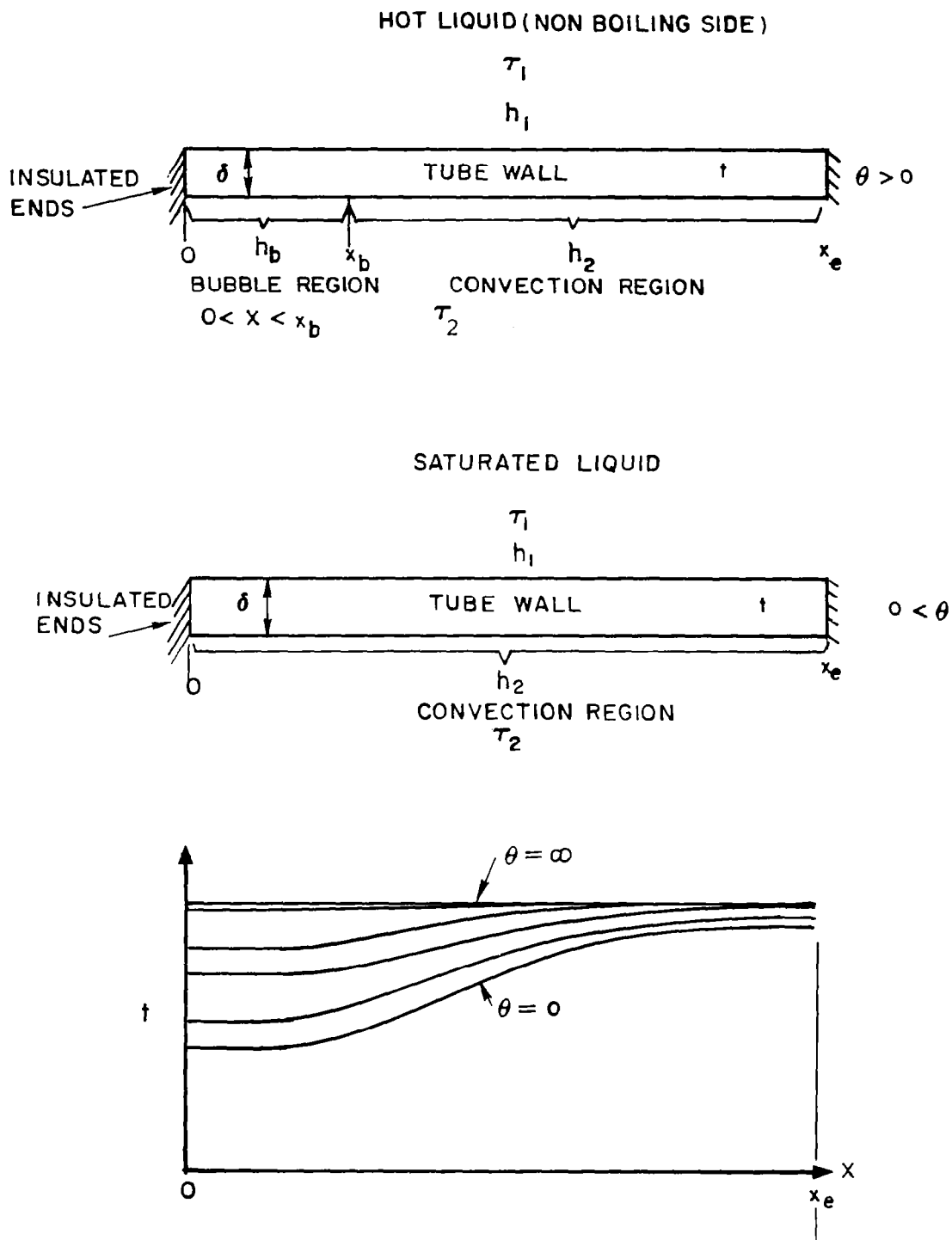


Figure V-21. Geometrical and temperature field representations for idealized boiling termination system.

α , thermal diffusivity of the boiler tube wall

k , thermal conductivity of the boiler tube wall

δ , thickness of the boiler tube wall

$$\alpha = \frac{h_1 + h_2}{k\delta}$$

The two boundary conditions for the system are,

$$\frac{\partial t}{\partial x} (x = 0, \theta) = 0 \quad (V-7)$$

$$\frac{\partial t}{\partial x} (x = x_e, \theta) = 0 \quad (V-8)$$

The initial condition (the steady state wall temperature profile for the non-uniform conductance profile on the saturated liquid side) is given by,

$$t(x, \theta = 0) = t_o(x) \quad (V-9)$$

where the solution to $t_o(x)$, derived previously at Geoscience, is

for $0 < x < x_b$

$$t - \frac{n_1}{\alpha_1} = C_1 e^{\sqrt{\alpha_1} x} + C_2 e^{-\sqrt{\alpha_1} x} \quad (V-10)$$

for $x_b < x < x_e$

$$t - \frac{n_2}{\alpha_2} = C_3 e^{\sqrt{\alpha_2} x} + C_4 e^{-\sqrt{\alpha_2} x} \quad (V-11)$$

where,

$$C_4 = \frac{\frac{n_2}{\alpha_2} - \frac{n_1}{\alpha_1}}{\frac{N_2 N_4}{N_3} - N_1} \quad (V-12)$$

$$C_1 = \frac{\frac{n_2}{\alpha_2} - \frac{n_1}{\alpha_1} + C_4 N_1}{N_4} \quad (V-13)$$

$$C_3 = C_4 e^{2\sqrt{\alpha_2} x_e} \quad (V-14)$$

$$C_1 = C_2 \quad (V-15)$$

and

$$N_1 = e^{2\sqrt{\alpha_2} x_e} e^{-\sqrt{\alpha_2} x_b} + e^{\sqrt{\alpha_2} x_b}$$

$$N_2 = e^{2\sqrt{\alpha_2} x_e} \sqrt{\alpha_2} e^{-\sqrt{\alpha_2} x_b} - \sqrt{\alpha_2} e^{\sqrt{\alpha_2} x_b}$$

$$N_3 = \sqrt{\alpha_1} e^{\sqrt{\alpha_1} x_b} - \sqrt{\alpha_1} e^{\sqrt{\alpha_1} x_b}$$

$$N_4 = e^{-\sqrt{\alpha_1} x_b} + e^{\sqrt{\alpha_1} x_b}$$

$$n_1 = \frac{h_1 t_h + h_b t_s}{k \delta}$$

$$\alpha_1 = \frac{h_1 + h_b}{k \delta}$$

$$n_2 = \frac{h_1 t_1 + h_2 T_2}{k \delta}$$

$$\alpha_2 = \frac{h_1 + h_2}{k \delta} = \alpha$$

From a physical standpoint, the temperature solution for this system should be of the form

$$t = t_{ss} + t_{tr} \quad (V-16)$$

The steady state term, t_{ss} , is equal to

$$t_{ss} = \frac{h_1 \tau_1 + h_2 \tau_2}{h_1 + h_2} \quad (V-17)$$

The transient term is the solution of the following boundary value problem:

$$-\alpha \frac{\partial t_{tr}}{\partial x} + \frac{\partial^2 t_{tr}}{\partial x^2} = \frac{1}{a} \frac{\partial t_{tr}}{\partial \theta} \quad (V-18)$$

$$\frac{\partial t_{tr}}{\partial x} (x = 0, \theta) = 0 \quad (V-19)$$

$$\frac{\partial t_{tr}}{\partial x} (x = x_e, \theta) = 0 \quad (V-20)$$

$$t(x, \theta = 0) = t_o(x) - t_{ss} = f_o(x) \quad (V-21)$$

The solution of Equation set (V-18), (V-19), (V-20), and (V-21), follows classical procedures. Let

$$t_{tr} = X(x) \cdot \Theta(\theta) \quad (V-22)$$

Substitution of Equation (V-22) into the differential equation yields,

$$\frac{X''}{X} = \frac{1}{a} \frac{\Theta'}{\Theta} + \alpha = -\beta^2 \quad (\text{V-23})$$

where β is a constant.

From Equation (V-23), there results

$$X = c_1 \sin \beta x + c_2 \cos \beta x \quad (\text{V-24})$$

and

$$\Theta = e^{-(\alpha + \beta^2) a \theta} \quad (\text{V-25})$$

where c_1 and c_2 are constants.

From the boundary condition at $x = 0$, the constant c_1 must be equal to zero. From the boundary condition at $x = x_e$,

$$0 = -c_2 \beta \sin \beta x_e$$

or

$$\beta = 0, \frac{\pi}{x_e}, \frac{2\pi}{x_e}, \dots \dots \frac{n\pi}{x_e} \quad (\text{V-26})$$

Thus Equation (V-22) becomes,

$$t_{tr} = \sum_{n=0}^{\infty} c_n e^{-(\alpha + \frac{n^2 \pi^2}{x_e^2}) (a\theta)} \cos \frac{n \pi x}{x_e} \quad (V-27)$$

From the initial condition, Equation (V-27) must reduce to $f_o(x)$ at $\theta = 0$, or

$$f_o(x) = \frac{c_o}{2} + c_1 \cos \frac{\pi x}{x_e} + c_2 \cos \frac{2 \pi x}{x_e} + \dots + c_n \cos \frac{n \pi x}{x_e} \quad (V-28)$$

where

$$c_n = \frac{2}{x_e} \int_0^{x_e} f_o(x) \cos \frac{n \pi x}{x_e} dx \quad (V-29)$$

Equation (V-28) is the classical half-range cosine series. Thus, Equation (V-22) becomes

$$t_{tr} = \frac{1}{x_e} \int_0^{x_e} f_o(x) dx + \frac{2e^{-\alpha a \theta}}{x_e} \sum_{n=1}^{\infty} e^{-\frac{\pi^2 n^2}{x_e^2} (a\theta)} \cos \frac{n \pi x}{x_e} \cdot \int_0^{x_e} f_o(x) \cos \frac{n \pi x}{x_e} dx \quad (V-30)$$

Therefore, the complete solution to boundary value problem defined by Equations (V-6), (V-7), (V-8), and (V-9) is given by the sum of Equations (V-17) and (V-30).

2. Wall Temperature Variations During Periodic Liquid Superheating

An analysis of the temperature history of the boiler wall during transient liquid superheating has been made in order to aid the interpretation of experimental transient temperature records. The model associated with this analysis is described below.

Idealized System

It is of value to consider the transient heat transfer and fluid flow processes that are in effect during periodic liquid superheating in the forced flow potassium boiling experiments under study at Geoscience. The electric power deposited in the boiler tube and the liquid metal increases the temperature of the flowing potassium to some degree of superheat in the exit region of the boiler. When the flashing process starts, the stored superheat is converted into latent heat resulting in the formation of vapor. In the boiling zone, the high velocity vapor is at the saturation temperature, while the contiguous tube wall temperature is rapidly approaching it. During the flashing process, hot boiler fluid can also be forced back into the preheater causing momentary flow reversals and increases in wall temperature (if the liquid superheating is large enough). After the wall temperatures in the boiler have decayed (during the flashing process), they will again rise, first at a rapid rate

because the vapor conductance is low, and then at a slower rate as liquid again flows through that portion of the boiler. The liquid and wall temperatures in the boiler then increase to a critical superheat value at which time the process repeats itself.

Analytical Description

Figure V-22 and Table V-V give an idealized description of the processes occurring in a forced flow boiler during periodic liquid superheating. The three, simplified processes (which would only occur at the boiler exit) are outlined as follows:

Step 1 to 2: At a thermocouple station near the exit of the boiler tube, the wall temperature (and the contiguous liquid) are superheated as a result of electrical or resistance heating in the tube and liquid. The process can be thought of as the charging of two condensers in parallel. The process stops when boiling starts.

Step 2 to 3: When boiling starts, the liquid flashes into a high velocity, saturated vapor almost instantaneously. During its expansion process, heat is transferred to the vapor from the boiler tube wall. This thermal process can be thought of as the discharge of a condenser through a very low thermal resistance.

Step 3 to 4: After the condenser has been discharged (and the liquid removed from the system by the high pressure vapor formed), the electrical heat generation again charges the system but this time the capacitor is defined only by the tube wall. When liquid reenters the

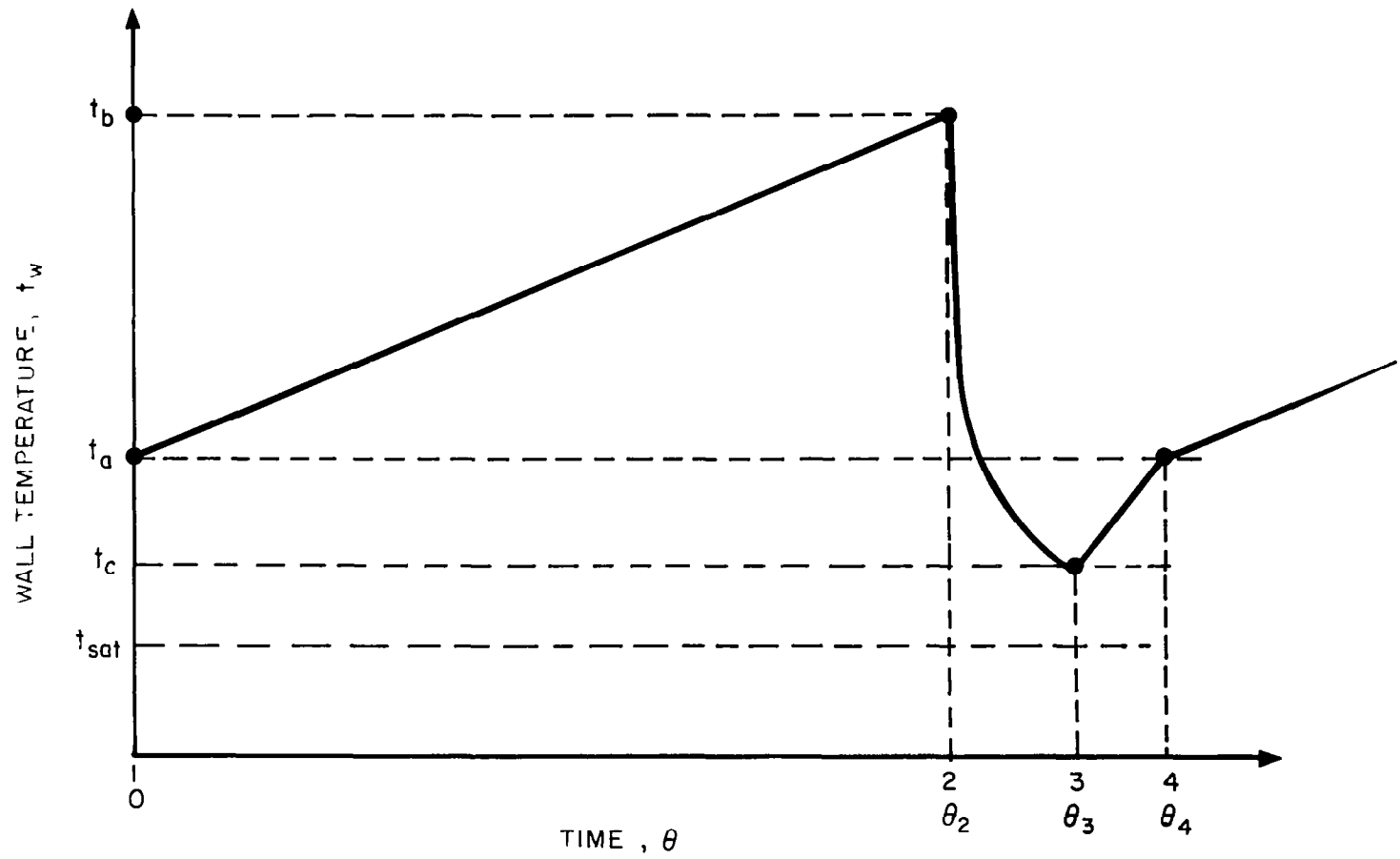
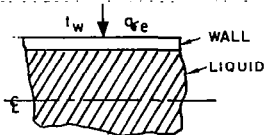
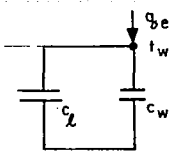
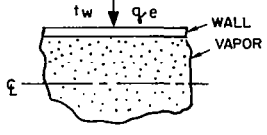
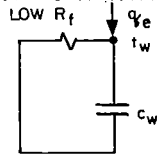
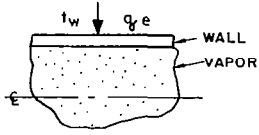
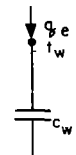


Figure V-22. Idealized transient wall temperature variation in a forced flow boiler with periodic liquid superheating.

TABLE V-V

Idealized Representation of the Processes Occurring
in a Forced Flow Boiler With Periodic Liquid Superheating

Process	Idealized System	Thermal Circuit	Wall Temperature* Solution
Step 1 - 2 in Figure 1; liquid superheating	 <p>Radial heat transfer is infinite (very high h_l); wall and liquid temperatures are the same. Axial convection is small.</p>		$q_e = (C_w + C_l) \frac{dt_w}{d\theta}$ $t_w - t_a = \frac{q_e}{(C_w + C_l)} \theta$
Step 2 - 3 in Figure 1; wall cooling immediately after the flashing of superheated liquid (vapor is expanding at high velocities)	 <p>Fluid temperature suddenly drops to the saturation value; high radial heat flow to high velocity vapor exists. Amount of vapor generated is determined by equating the stored liquid superheat to the latent heat transfer.</p>		$q_e = C_w \frac{dt_w}{d\theta} + \frac{t_w}{R_f}$ $t_w = R_f q_e - (R_f q_e - t_b) e^{-\frac{\theta - \theta_2}{R_f C_w}}$
Step 3 - 4 in Figure 1; wall heating after vapor expansion (high convective resistance) just prior to reentry of liquid flow	 <p>Radial heat transfer considered negligible (very low h_{vap})</p>		$q_e = C_w \frac{dt_w}{d\theta}$ $t_w - t_c = \frac{q_e}{C_w} (\theta - \theta_3)$

* Note: All wall temperatures, t_w , are defined in terms of the excess above the saturation temperatures.

boiler tube where the temperature is being measured, the system thermal capacity is again defined by the wall and liquid. The charging process now proceeds at a much lower rate and is a repeat of step 1 to 2.

An illustrative, experimental time-tube wall temperature trace obtained during an all-liquid-fill potassium boiling inception experiment at Geoscience is shown in Figure V-23. Note the similarities between some of the wall temperature measurements and the idealized profile shown in Figure V-22. The feature of momentary reverse flow during the flashing process in the boiler has also been verified experimentally by sudden wall temperature increases in the preheater as a result of the inflow of hot liquid from the boiler region.

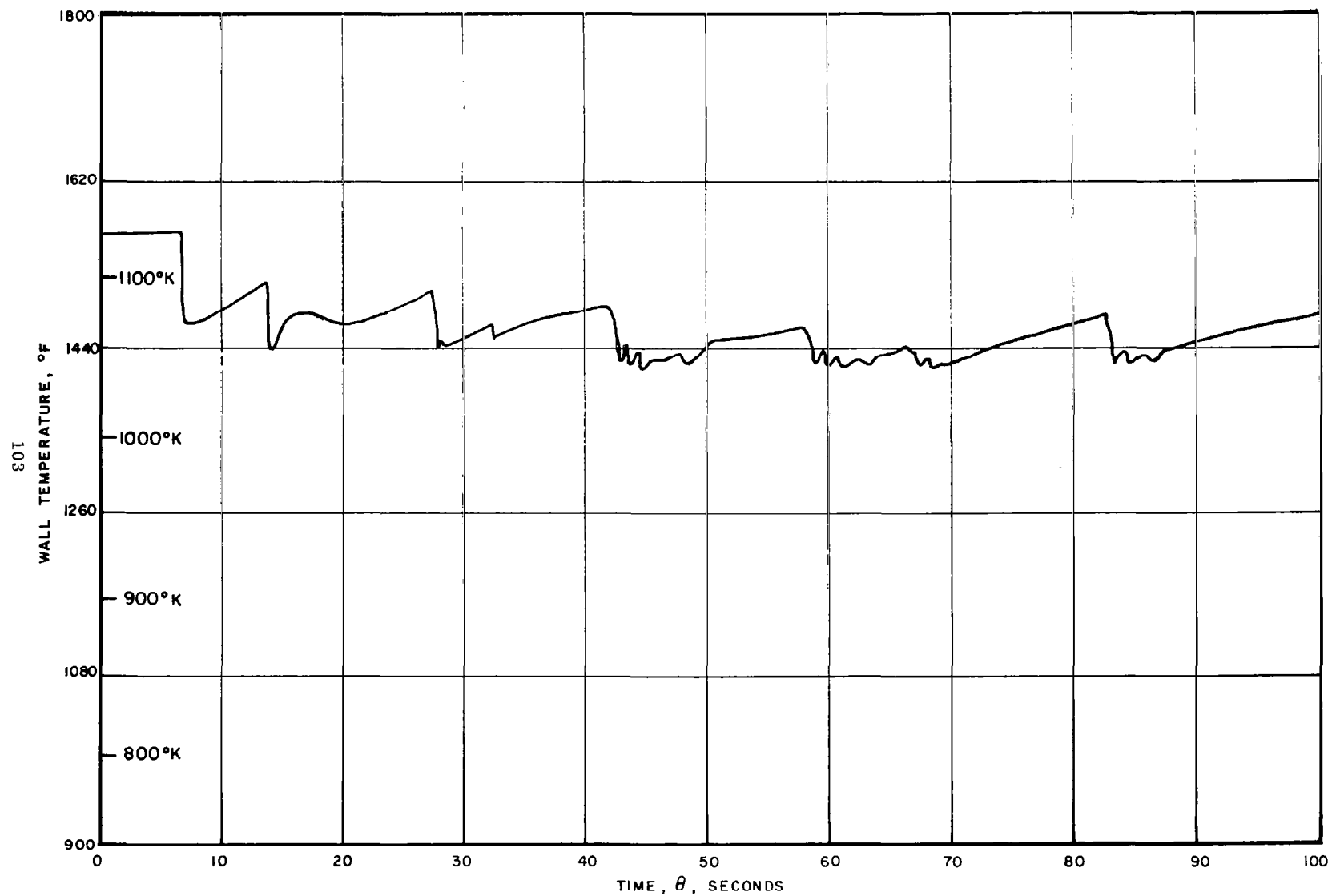


Figure V-23. Experimental time-tube wall temperature trace obtained during liquid superheating studies.

C. Discussion of the Present Data

A considerable range of several variables was covered in the experimental work. Specifically, the parameters were

Saturation temperature:	949°F to 1556°F
Velocity in test section inlet:	0 to 4.18 feet per second
Residual inert gas level after fill:	36×10^{-3} torr to .3 psia
Dissolved gas in potassium:	degassed and saturated
Fill liquid temperature:	800°F to 1104°F

One would hope to be able to establish the effects of all of these parameters upon the two superheats from the experimental data obtained. However, this was not possible because of the large number of combinations of the controlling parameters. There are a number of aspects of the experimental work which make interpretation of the parametric effects difficult.

An example of one of these is shown in Figure V-24 , which is a copy of the temperature record at a station near the boiler outlet, recorded over several minutes during one of the more stable runs. At the beginning of the first line of record, the temperature may be seen rising steadily to a point far above the saturation temperature, and then dropping rapidly as the first change of phase occurs. The incipient superheat at this point is 204°F. The record continues, indicating large amplitude temperature fluctuations, as much as 110°F high and several seconds long. These fluctuations gradually decrease in amplitude until a relatively small amplitude, repetitive fluctuation indicates what we have referred to as nucleate boiling. The typical superheat in this region, lines four and five of the data in the figure, is about 17°F. However, it is not precisely steady,

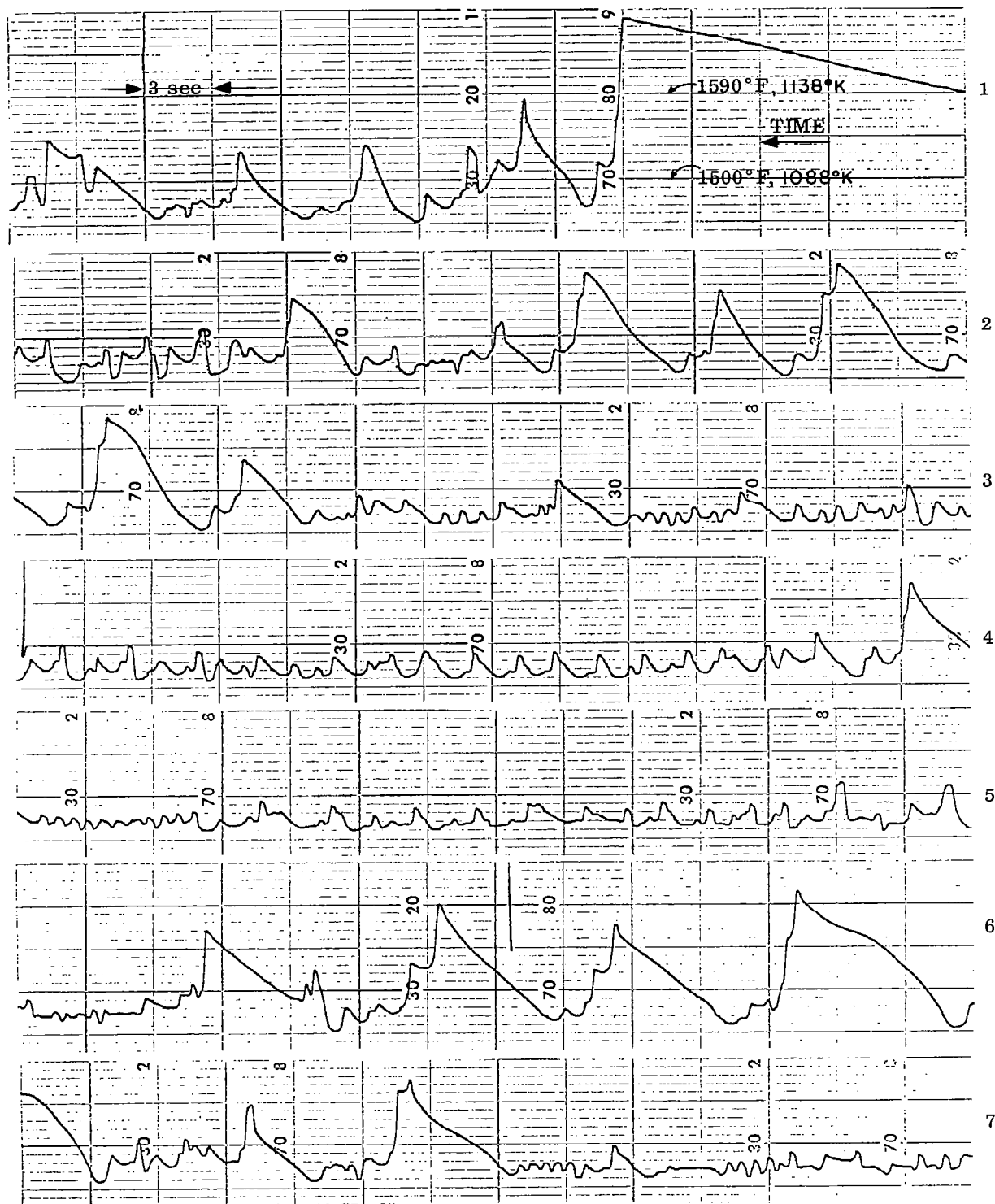


Figure V-24. Temperature-Time Record for Thermocouple Number 18
All-Liquid Fill, Saturation Temperature 1071°K 15:42, Sept. 14, 1971.

and at the very end of line five there begins a change which leads to very large amplitude temperature fluctuations. These large fluctuations decrease through line seven to approximately the same "nucleate boiling" level as before. All of the changes occur in the absence of any intentional changes in the system controls, and with no apparent change in flow rate, saturation temperature or any other measured parameter. One might suspect that the system is still accommodating itself to the new power level and that these variations would eventually damp out. This does not appear to occur over periods of one hour.

There is a problem of suitable averaging time for measurement of nucleate boiling superheat in the example run of Figure V-24 and other runs with similar histories. Other runs exhibited temperature behavior which consisted entirely of large amplitude, long period (eight to 30 second) temperature fluctuations similar to those of line two, Figure V-24. In the case of fluctuations with a 30 second cycle, it is not clear that there is a difference between "incipient superheat" and "nucleating superheat," since there cannot be any vapor mixed with superheated liquid anywhere in the boiler for time periods this long.

Changes of phase associated with large amplitude temperature fluctuations, such as those in line two of Figure V-24, cause violent changes of pressure and fluid acceleration throughout the flow system, and a clearly audible metallic clang is associated with these events. During all of the data runs the valve and flow restriction at the preheater inlet were set for a high pressure drop, very near the capability of the pump (30 psi) in order to provide the maximum flow damping. The largest two-phase

pressure drop for any of the runs was an order of magnitude below the flow restriction pressure drop. Despite this flow damping, flow reversals were still indicated by the EM Flowmeter during the more violent phase change events. An example of such a flow reversal is shown in Figure V-25, which presents a combined temperature flow rate record. The temperature record is from one of the tungsten-rhenium thermocouples, in this case placed about four inches below the boiler outlet. A flow reversal lasting approximately one-half second can be seen near the right edge of the second line of EM flowmeter output. This correlates in time with the sudden drop in temperature shown in the second line of the temperature record. Many other phase change events, and their corresponding flow change records, can be seen in the figure also.

Careful inspection of the figure will indicate that the initiation of the flow disturbance and the temperature disturbance do not exactly coincide in every case. The reason for this is that the change of phase does not necessarily occur directly under the thermocouple, and although the pressure wave which affects the flow is transmitted almost instantaneously, the front between the liquid and vapor travels more slowly. This front probably travels at the local (accelerating) liquid velocity. The vapor bubbles are constrained by the inertia of the surrounding liquid, so that their internal pressure must increase rapidly with the change of phase of additional superheated liquid. The rising pressure must suppress additional vaporization until the vapor can expand at the rate determined by the motion of the liquid.

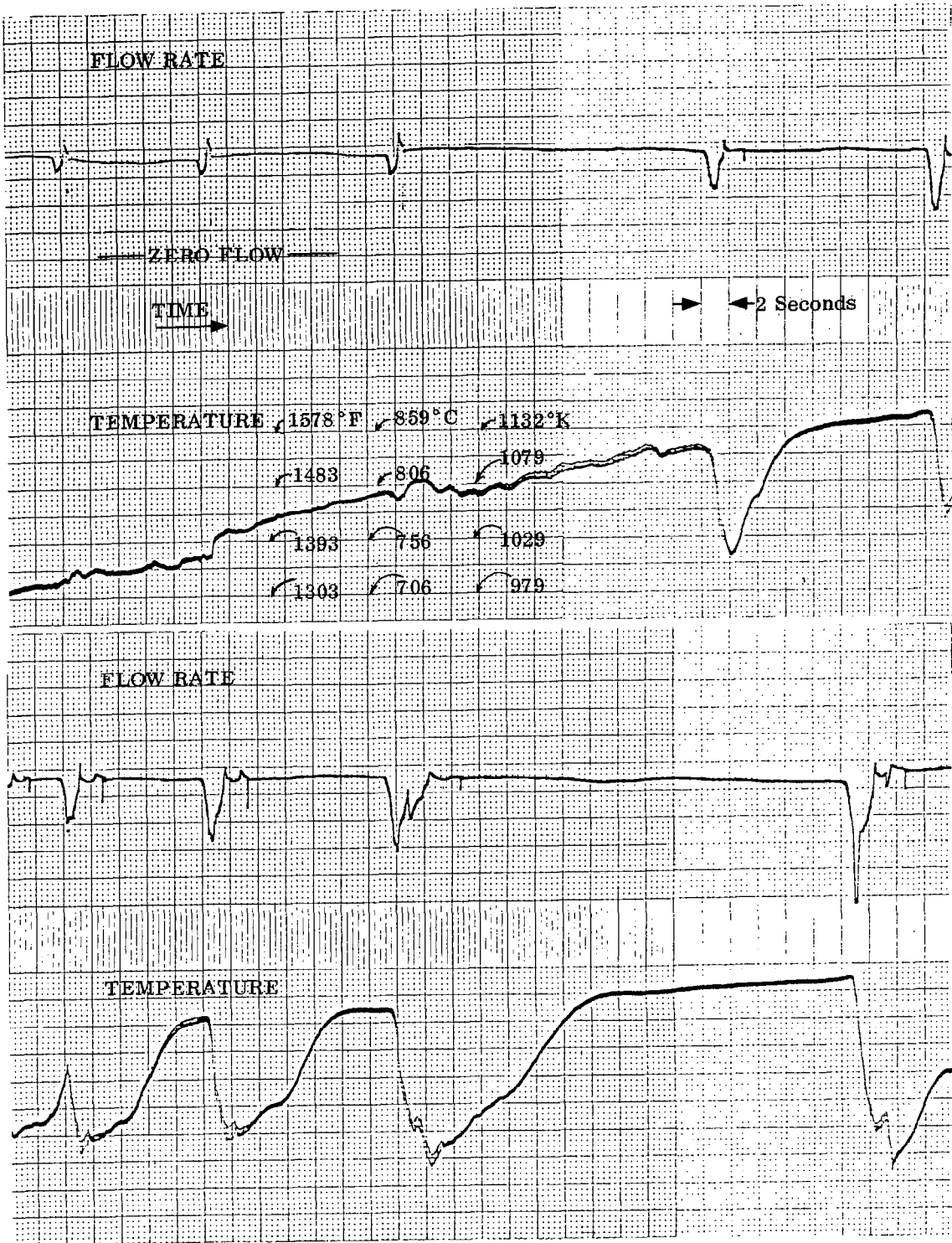


Figure V-25. Temperature-Time Record and EM Flowmeter Record
All-Liquid Fill, Saturation Temperature 1022°K 15:27, Sept. 14, 1971.

Location of Phase Change in the Boiler

Two different methods of system start up, all liquid fill and two phase fill, have been utilized in the experiments. In the all-liquid-fill start-up, the initial formation of vapor is constrained to a location submerged in liquid. In the two-phase fill start-up, the formation of vapor can occur also at the liquid-vapor interface. In none of the two-phase fill experiments was boiling observed to occur at the interface. The locations of boiling initiation were submerged in the liquid in all of the runs made with this apparatus. No consistent location for the change of phase was observed. Boiling inception was observed at all elevations in the boiler and did not appear to correlate with location of maximum liquid temperature. This latter location was usually near the exit end of the boiler.

Effect of Rinse-Fill Process

Before the first boiling inception run was made, a "rinse-fill" of pure potassium was circulated through the system and drained. This potassium was introduced hot and degassed, after the system was evacuated, and baked out at 10^{-4} torr. Because of the careful cleaning processes, the rinse material probably wet the walls of the boiler and under such conditions could be expected to fill almost all surface cavities. No normal draining process could be expected to remove the wetted surface film of liquid metal from the boiler walls. It, therefore, appears that most potential nucleation sites were never accessible to the residual inert gas introduced into the system before the experimental runs.

The procedure used before each fill process was to evacuate the flow circuit to the chosen residual gas pressure level after the boiler had been preheated to the chosen fill temperatures. Under some conditions of pressure level, temperature level, and pump down time, a significant portion of the potassium wetted film on the walls would be expected to evaporate, leaving some nucleation sites accessible to the inert gas. This combination of circumstances introduces an uncontrolled variable into the experiment which may possibly affect the results.

Effect of Saturation Temperature Upon Superheat

Sufficient data are available from the experiments to show the variation in nucleating superheat of changes in saturation level. Figure V-26, which presents these data, indicates that, for the conditions shown, the nucleating superheat decreases with increasing saturation temperature. There does not appear to be a large effect of either fill liquid temperature nor dissolved gas level upon this superheat.

Effect of Liquid Velocity Upon Superheat

Sufficient data are available from the experiments to show the variation in nucleating superheat versus liquid velocity. Figure V-27, which presents these data, indicates that the nucleating superheat decreases with increasing flow velocity. This is in agreement with results from other workers. Again it may be seen that little change is affected by variation in fill liquid temperature or dissolved gas level.

III

Liquid Superheat, °F

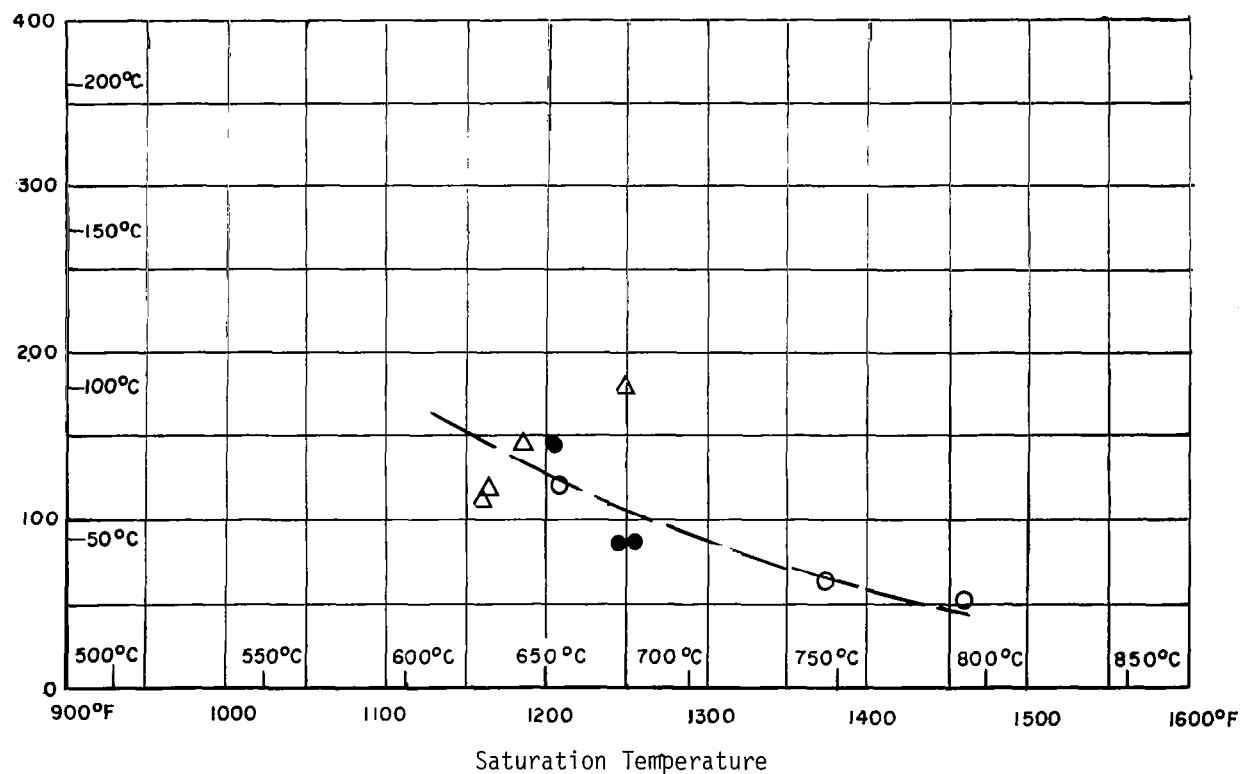


Figure V-26. Nucleating superheat versus saturation temperature two-phase fill, residual gas level 0.03 to 0.05 psia

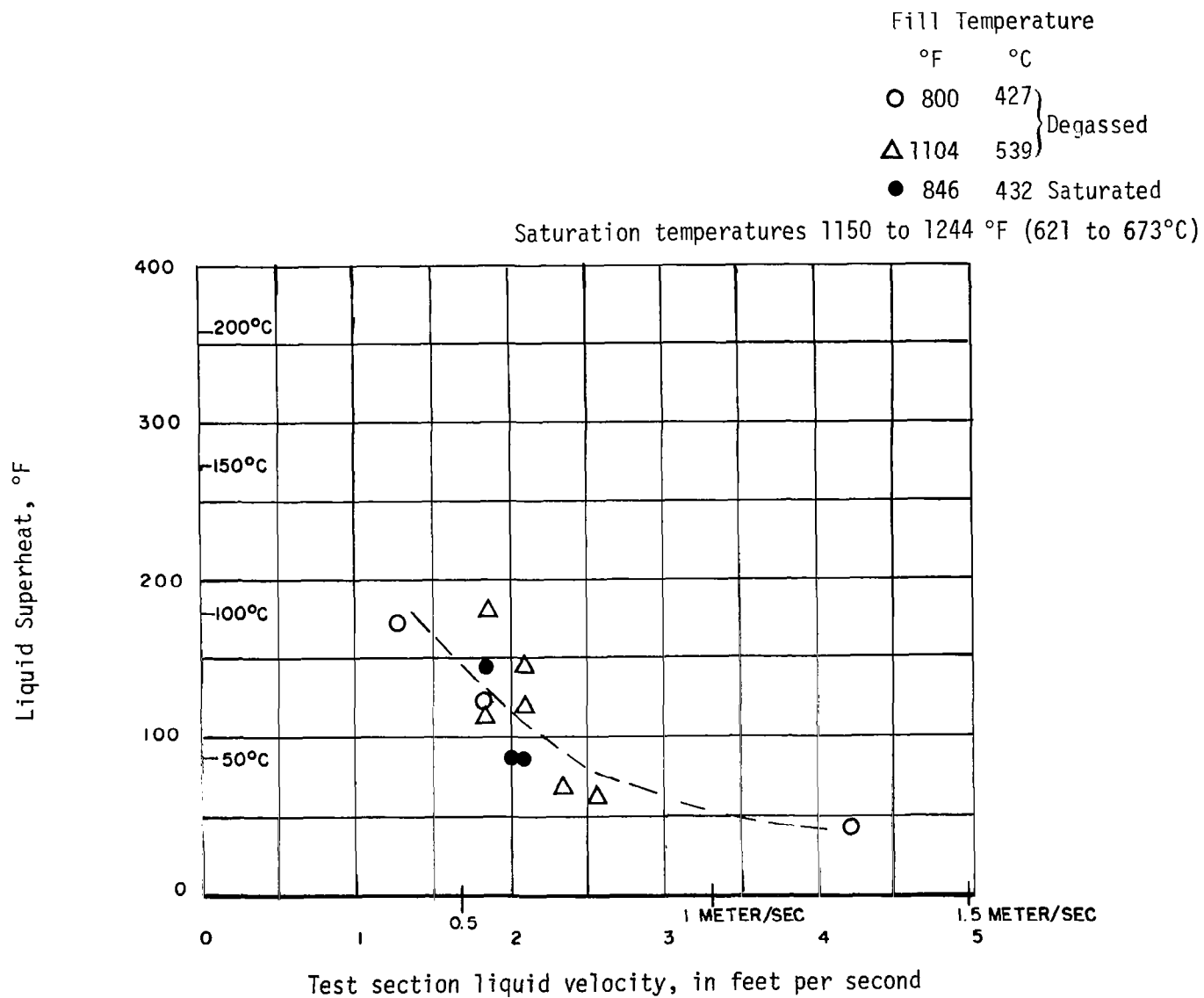


Figure V-27. Nucleating superheat versus velocity two-phase fill, residual gas level 0.03 to 0.05 psia

There is a gross difference in the appearance of temperature traces taken at low flow velocity and high flow velocity. When the superheat temperature ΔT_{SH} is low, the time between temperature oscillations is small, while large superheat temperatures usually are associated with long temperature oscillations. The rate of rise of fluid temperature in the absence of boiling is fixed by the combination of power level and flow rate, and this combination cannot be varied over a very large range. Large superheats lead to much more violent phase change processes, with accompanying flow rate variations.

Some data were taken at zero average flow velocity which could not be plotted on the graph of Figure V-27 because the points do not fall within acceptably narrow limits in the other variables. Under zero average flow conditions, the change of phase repetition times are frequently so long that a reasonable definition for "nucleating" superheat cannot be established, and superheats of hundreds of degrees have been observed. It seems clear that the liquid superheat condition, in common with other metastable systems, such as laminar flow at supercritical Reynolds moduli, is affected by flow disturbances.

Effect of Residual Inert Gas Pressure Level

There does not appear to be any consistent effect of residual inert gas pressure level. Some of the lowest and highest superheats in the experimental

program were observed with either extreme in this variable. Expectations based on current boiling nucleation theory are that this variable would be one of the most significant. This possibility is not eliminated by the present results. As observed in the discussion of the rinse fill, the interior wall of the boiler and the surface of the helical vane are both probably wet by the potassium and coated at nearly all times. The fill liquid is introduced from the bottom, and would be expected to displace the inert gas almost completely as it rises in the boiler. Since there are few, if any, cavities to trap the gas, it all is pushed up into the free space above the liquid (in the case of a two-phase start-up). Since all observed phase change processes occurred at locations submerged in the liquid, this displaced gas cannot have had any effect on the magnitude of the liquid superheat.

Gas trapped by the liquid at the highest point in the system during an all-liquid-fill run would be expected to be carried around the circuit if the flow rate is sufficiently high, and since for these runs the supply reservoir valve is open, and leads off from the top of the flow circuit tubing, this entrained gas is eventually collected in the reservoir and removed from the circuit. Gas which is entrained in the flow during a two-phase fill, on the other hand, cannot be deposited in the reservoir since the valve is closed. In several runs with very high residual gas level, this entrained gas was carried continuously around the circuit, and could be observed by the audible noise in the electromagnetic pump and by aberrations in the output of the electromagnetic flowmeter. These runs tended to have very small nucleate superheat levels, but flow rates were difficult to establish and impossible to maintain steady because of gas blanketing in the pump, so no data from these runs are plotted.

VI. CONCLUSIONS

A test program was conducted to survey the problem of gross liquid superheat in a potassium boiler. The magnitude of exit liquid superheat observed ranged from 43°F to 264°F. The highest superheats generally occurred at lower saturation temperatures and at low liquid velocities. There did not appear to be a large effect of either fill liquid temperature nor dissolved gas level upon the superheat measured. The data presented will assist in selecting saturation temperatures and flow velocities for boiler startup with minimum superheat problems.

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VIII. NOMENCLATURE

a	=	dimension, inches
h	=	dimension, inches
p_b	=	pressure inside bubble, psia
p_g	=	inert gas pressure, psia
p_ℓ	=	local pressure in liquid, psia
p_v	=	vapor pressure, psia
q	=	surface roughness ratio
r	=	bubble radius, inches
R^*	=	minimum radius of curvature, inches
T_{inc}	=	local liquid temperature at incipient boiling, °K
T_s	=	saturation temperature, °K
T_w	=	wall temperature at liquid interface, °K
T_v^*	=	saturation temperature corresponding to p_v , °K
β	=	contact angle, degrees
σ	=	surface tension, lbs/inches

APPENDIX I: TEST PLANS

The experimental program was conducted according to the two test plans which are reproduced here.

A. Test Plan: All Liquid Fill

There are specified in the work statement for the all-liquid fill three residual gas levels, three fill temperatures, three levels of dissolved gas in the potassium, and a range of saturation temperatures and liquid velocities. The initial test program includes a separate liquid fill for at least one variation of all of the parameters considered to be important. These variations are listed in Table A-I. It may be necessary to modify the sequence or variety of the runs, depending upon the outcome of individual parameter variations.

If, after this sequence, no liquid superheating is observed, or if the observed superheat does not appear to be related to any of the controlled variables, the all-liquid fill tests will be temporarily terminated and two-phase fill experiments begun.

The test program outlined in Table A-I requires nine separate liquid fills. The parameter variations listed refer to the fill conditions and to the conditions which will be maintained during the first boiling test after each fill. After the first onset of boiling, a number of parameter variations

TABLE A-I. PLANNED ALL-LIQUID FILL RUNS.
EACH RUN CONSTITUTES A SINGLE FILL OF THE POTASSIUM CIRCUIT.

Run Number	Liquid Fill Temperature °F	Potassium Velocity Ft/Sec	Saturation Temperature °F	Residual Inert Gas Pressure Level psia	Dissolved Inert Gas Level
1	800	3	1400	0.1	degassed
2	800	3	1400	0.1	degassed
3	800	3	1400	0.1	degassed
4	800	0.5	1400	0.1	degassed
5	800	3	1200	0.1	degassed
6	800	3	1600	0.1	degassed
7	800	3	1400	0.01	degassed
8	800	3	1400	0.1	saturated
9	1200	3	1400	0.1	degassed

NOTES: 1) This schedule includes at least one variation of all parameters considered to be important. It is subject to a change if a particular parameter has a strong effect on boiling inception.

2) The first two runs have different paths to boiling. In No. 1, the boiling will be achieved by setting the flow rate, and increasing heat flux until boiling begins. In No. 2, boiling will be achieved by setting the heat flux and reducing the flow rate until boiling begins. The third run will be a repeat of number 2 to test repeatability. During each of these runs, saturation pressure and flow rate will be varied in an orderly manner in order to determine characteristics of boiling inception without refill.

can be made, using the same fill liquid. Such parameter variations are included in the typical run described below.

Liquid Fill Runs

A typical fill run will be performed as follows: The reservoir will be solidly filled with high purity potassium. The upper valve 31 will then be opened to allow pressure monitoring and to allow expansion of the potassium liquid. The level of dissolved gas will be set by the procedure described under that heading. The reservoir will be pressurized to 5 to 10 psig. The liquid in the reservoir will then be heated to 800°F (1200°F) (1400°F). The preheater boiler unit will be preheated to the same temperature and evacuated to establish the residual inert gas pressure level. Valve 1 will then be opened to fill the flow circuit with potassium. The potassium will be circulated at a fixed flow rate while increasing the power to the preheater and boiler slowly to increase the temperature. Continuous recordings will be maintained on supply tank pressure, boiler temperature, and potassium flow. The saturation pressure will be set by argon pressure at the top of the reservoir. The boiler temperature will be raised until boiling occurs. The boiler power will be increased above this point 15 percent for a period of time long enough to ensure thermal equilibrium. The power will then be decreased until boiling ceases. The power will again be increased to bring about boiling, maintained above boiling and decreased. This procedure will be repeated several times to observe the reproducibility of the boiling inception temperature.

The flow rate will then be changed while the reservoir pressure is held constant, and the temperature raised to bring about boiling, and again repeated. Three or more flow rates, spanning the limits of the experimental equipment, will be tested. The supply tank pressure level will then be changed and the various procedures repeated.

Subsequent fill operations will determine whether the procedure of stopping boiling and changing flow rates, as described above, yields the same superheat results as refilling and initiating boiling for the first time with new material.

The potassium in the flow circuit will then be returned to the reservoir or drained. Enough potassium is held in the reservoir to fill the flow circuit three times if the liquid is drained after each run.

Although it is possible to return the circuit charge to the supply tank for reuse, it appears that the possibility of contamination of the loop is lessened by discarding the charge. Therefore, the all-liquid-fill outlined will require four fill processes for the supply tank.

Potassium Rinse

The following procedure will be followed before initiation of any tests. The boiling potassium system will be assembled clean, evacuated and baked at low temperature ($\sim 200^{\circ}\text{F}$) until a vacuum of 10^{-4} torr can be maintained. The facility will be flushed with pure argon and evacuated several times. During periods of shutdown, the system will be maintained above atmospheric pressure.

The initial fill will be a rinse, using high purity potassium. The procedure will be as follows: The reservoir will be filled solidly with potassium with both the upper and lower valves (No. 1 and 31) closed. The flow circuit

will then be evacuated to 10^{-4} torr and heated to 200°F. The top of the reservoir will then be pressurized with argon to 20 psig with valve 31 open and the lower valve (1) opened to allow potassium to flow into the entire circuit and fill it solidly full. This charge will be circulated for several hours. During this period, various items of instrumentation and equipment will be tested and the electromagnetic flowmeter will be calibrated using the thermal flowmeter. The flow circuit and supply tank will then be drained completely and the system filled with argon and cooled.

Heat Loss Measurements

Before initial filling of the system with potassium, the potassium circuit will be pumped to the lowest pressure possible and baked out by heating all parts of the loop, using all of the circuit heating equipment. During this heating cycle, heat loss measurements will be made to determine the performance of the radiation shielding. These measurements will be adequate to provide graphs of heat loss versus tube wall temperature, which can be used during reduction of the boiling run data to correct heat fluxes and energy balances.

Preheater-Boiler Electrode Guard Heater Settings

It is expected that during this experimental program, potassium boiling will be limited to the straight section of tubing above the main power centertap electrode and referred to in the drawings as the boiler. During a large portion of the runs, the boiling will probably be confined to the upper end of this straight section, so that the lower portion of the "boiler"

will actually serve as a preheater as well as the portion of the continuous tube referred to in the drawings as the "preheater." The fluid flowing in the tube through both the centertap and the lower electrodes will, therefore, be subcooled liquid. It may be shown that the temperature difference between the liquid mixed mean and the tube inside wall temperature and the temperature drop across the wall are both small for heat fluxes of the level which will be imposed during these experiments. The guard heaters on the centertap electrode and the lower ground return electrode will, therefore, be adjusted so that the electrodes are at the same temperature level as the surrounding tube, as nearly as can be determined. Although variations in this adjustment can cause local flows of heat in or out of the fluid, this will have negligible effect on the quality of the energy balance determination since the fluxes under the electrodes will be small, and the area in which the fluxes will be unknown is a small portion of the total area ($\sim 1\%$).

The tube clamped into the upper ground return electrode, which is positioned between the upper end of the boiler and the two-phase temperature determination section, will have a superheated liquid or two-phase mixture flowing through it during the experiments. The electrode area, although small, could, under some circumstances, interfere with the conduct of the experiments, particularly if a large amount of heat were conducted into the fluid under this electrode, since this condition could lead to the onset of boiling at a location where the wall temperature is not well determined. In order to prevent this occurrence, the electrode temperature will be maintained, insofar as possible, at the local temperature of the liquid. If boiling occurs somewhere in the boiler, the electrode will be maintained at the saturation temperature.

Setting the Dissolved Gas Level in the Potassium

It appears that tests of the two extremes, degassed and saturated, should be performed before any intermediate points. From reference A-1, it appears that the solubility of argon in potassium increases at higher temperature. Therefore, the saturated case will be done by bringing the liquid metal to the fill temperature and bubbling argon through the metal (using the dip tube in the reservoir installed for that purpose) for a period of one-half hour. The potassium will then be assumed to be saturated with argon and the fill procedure will be initiated.

The degassing procedure will involve boiling in the reservoir at a temperature of 800 to 1000°F, using the water-cooled tube above the reservoir as a condenser so that the condensed liquid returns to the reservoir. After boiling the liquid vigorously for a period of one hour, the liquid will be assumed to be degassed and the circuit fill procedure will be initiated. If no difference appears in the boiling inception in two runs identical except for dissolved gas level, it is suggested that the remainder of the tests be run with the liquid as it is filled in the reservoir.

Estimated Time for Completion of Liquid Fill Runs

Approximately one working day for three men will be required for each of the nine runs listed. This includes the filling and draining procedures for each run but does not include the reservoir filling process. This procedure is expected to require two men for one-half a working day.

Table A-II. Planned Two-Phase Fill Runs. Each run constitutes a single fill of the potassium circuit.

Run Number	Liquid Fill Temperature °F	Potassium Velocity, * ft/sec	Residual Inert Gas Pressure Level, psia	Dissolved Inert Gas Level
1	800	3	0.1	degassed
2	800	3	0.1	degassed
3	800	3	0.01	degassed
4	800	3	0.1	saturated
5	800	0.5	0.1	degassed
6	1200	3	0.1	degassed

After each of these runs, the power level will be decreased and then brought back up to determine characteristics of boiling inception without refill.

*Approximate liquid potassium velocity at inlet to boiler at a saturation temperature of 1400 °F. Velocity cannot be controlled independently. See section entitled "Control of Test Variables in a Forced Convection Boiling Circuit."

B. Test Plan: Two-Phase Fill

The test series described here consists of six separate fill processes, which include changes in all of the variables believed to be important in boiling inception. Table A-II lists the principal parameter variations to be included. The program begins with two identical "datum" tests, the second of which is required to check reproducibility of the process. Subsequent tests vary each of the controllable parameters individually so that the effect of each one may be determined independent of the others.

The controlled variables are: liquid fill temperature, amount of dissolved gas in the fill liquid, saturation temperature, liquid potassium velocity in test section, and residual inert gas level in the system before fill. It may be observed that no separate listing of saturation temperature variation is included in Table A-II. The method of testing required to satisfy the work statement includes a sweep through a range of saturation temperatures for each fill process.

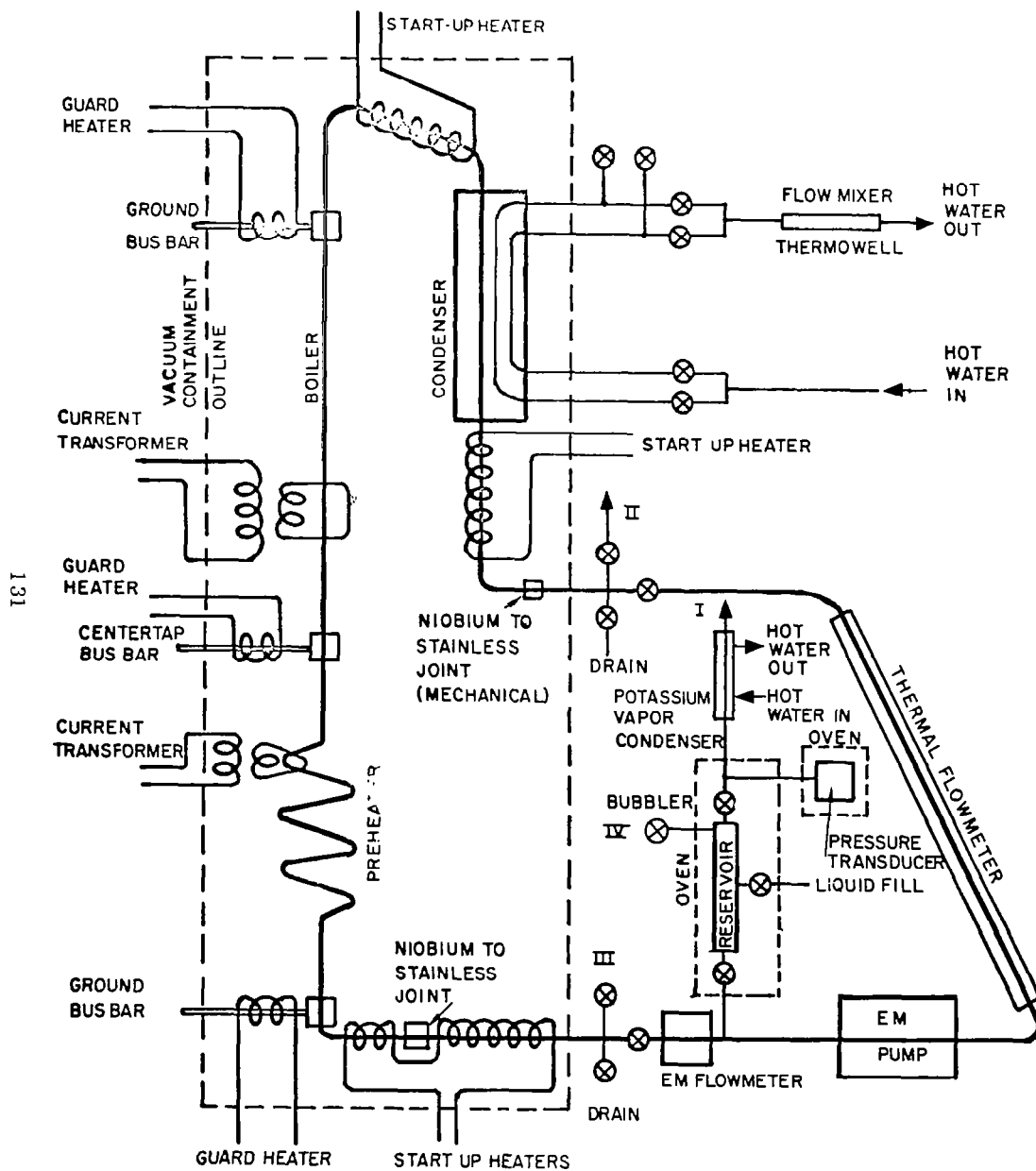
The parameter variations listed in Table A-II refer to the fill conditions and to the conditions which will be maintained during the first boiling test after each fill. After the first sweep through a range of saturation temperatures, a number of parameter variations can be made, using the same fill liquid. Such parameter variations are included in the typical run described below.

Two-Phase Fill Runs

A typical fill run will be performed as follows: The reservoir will be solidly filled with high purity potassium. The upper valve on the reservoir will then be opened (see Figure A-1) to allow pressure control and to allow expansion of the potassium liquid. The level of dissolved gas will then be set by the procedure described under that heading in the All-Liquid Fill Test Plan. The reservoir will then be pressurized to 5 to 10 psig. The liquid in the reservoir will be brought to the appropriate fill temperature. The preheater boiler unit and coupling tubing will be preheated to the fill temperature, and evacuated to establish the residual inert gas pressure level.

The system is now ready for the fill process. Potassium will be introduced to bring the liquid to a given level by opening the valve at the bottom of the reservoir a very small amount, so that the potassium flows out slowly and rises in both the preheater and in the thermal flowmeter. After the liquid has reached a predetermined level, determined by the electrical resistance characteristics of the boiler, the valve will be closed at the bottom of the reservoir.

The electromagnetic pump will be brought up to a current which will maintain a small pressure head between the boiler and condenser. The system will now be in a steady boiling condition at reduced pressure, since the condenser temperature will be regulated by the cooling water temperature of 180°F and the boiler will be at the fill temperature many hundreds of degrees higher. The mass flow rate will be determined by the equality between



Notes:

- 1) Points indicated with Roman numerals connect to similarly numbered points on manifold. (SEE FIG. II-II)
- 2) Start up heaters external to vacuum containment are not shown.
- 3) Electrical power is required for
 - a) preheater-boiler
 - b) guard heaters
 - c) start up heaters
 - d) EM pump
 - e) thermal flowmeter
 - f) reservoir oven
 - g) pressure transducer oven

Figure A-1. Schematic diagram of potassium circuit.

the two phase pressure drop and the difference in saturation temperature between the boiler and condenser. Small step increases in the power level will increase the liquid mass flow and the saturation temperature together, and small step increases in the electromagnetic pump current will maintain the liquid level in the boiler. These increases will be made until the saturation temperature has reached a predetermined maximum level. The saturation temperature, therefore, sweeps through all of the temperatures between the fill temperature and the test maximum. Since the liquid level is maintained at a fixed point in the boiler, the wall temperature profile will determine the liquid superheat in steady state.

After the complete range of saturation temperatures has been covered, the power level will be reduced and the entire process repeated to test boiling inception without refill, as has been the procedure with the all-liquid-fill tests.

Although it is possible to return the circuit charge to the supply tank for reuse, it appears that the possibility of contamination of the loop is lessened by discarding the charge. Enough potassium is held in the reservoir to fill the flow circuit to the two-phase fill level four times if the liquid is drained after each run.

Control of Test Variables in a Forced Convection Boiling Circuit

The operator of a forced convection boiling circuit has a number of variables over which he has control. Dependent upon the specific components included in the system, these may be heater voltage, pump pressure rise, throttling orifice size, condenser coolant temperature, amount of liquid charge, or

others. The system to be controlled has a number of characteristics which were determined at the time of design, which affect the operation but over which the operator has no control, such as flow passage size, tube wall thickness (which affects the thermal time constants), condenser areas, etc.

In a typical boiling system, the operator does not have direct control of many of the variables of interest in the system operation, but must instead adjust the parameters under his direct control to obtain values of the variables which are acceptable. Consider, for example, a circuit containing an electromagnetic pump, a preheater, a boiler, a flow resistance between boiler and condenser, and a condenser. It is desired to control mass flow rate and boiler saturation temperature. The pump, however, provides an adjustable pressure rise which, for a wide range of conditions, is independent of mass flow rate. The mass flow rate is, therefore, determined by an equality between the pressure drop around the circuit and the pressure rise in the pump. The pressure drop is related to the boiler exit quality, which is a function of power input, the initial fill level in the circuit (which determines the effective condenser area), the saturation temperature in the condenser (which determines the vapor density and the driving potential for heat transfer), and others.

If the operator can only control pump pressure rise and power level during operation, then mass flow rate and saturation temperature are coupled. These two variables can be controlled separately only by adjusting the liquid fill level.

It is possible to analytically describe the performance of a system such as that described above not only for fixed conditions, but when subjected to transients as well.* However, for the present purposes, where a range of variables are to be covered, an experimental successive approximations approach to some desired operation conditions would probably be fruitful.

The experimental system to which this test plan applies is similar to the system described above. It can be seen that a given test run, as described in this plan, where the saturation temperature is swept through a range of values, will also have a sweep through a range of flow rates and boiler exit qualities.

* See, for example, GLR-39.

APPENDIX II: SAFETY AND HEALTH PLAN

Safety Plan

All potassium boiling experiments are conducted in a 10 x 10 x 10 foot double steel walled room with continuous external ventilation. All potassium handling is done inside the steel room. The total amount of potassium in the heat transfer system is less than two pounds. The largest quantity of potassium on hand is a ten-pound shipping container located inside the room. A steel floor cools all molten potassium in the event of spills. The shutoff valve for the potassium is located outside the steel room. In addition, shutoff controls will be used. A potassium fire extinguisher containing dry chemicals is on hand and the steel room contains ports for system observation during the experiments. Masks, suits, and gloves for cleanup are available.

Health Plan

The two prime hazards in connection with potassium fires are (1) inhalation of reaction product fumes (KOH, etc.), and (2) burns as a result of the molten metal. The double-walled, externally-ventilated steel room protects the personnel from these two hazards because no one will be allowed to enter the room until the fires are out and the fumes are cleared. Before entry into the room, after the fires and fumes no longer exist, the company personnel are also required to wear masks and protection clothing as a dual safety step.

Procedures

In order to assure safe operation when working with molten potassium, specified

material transfer, start-up, operation, shutdown and dismantling procedures are followed. The steps involved in supply tank filling and system draining (the prime procedures) are detailed below:

Check List for Supply Tank Filling

1. Weigh shipping container.
2. Remove cap from fill connection on supply tank, install shipping container jumper to fill valve. (Shipping container is installed in pump oven but do not connect at this time.)
3. Disconnect surge tank and pump vent lines at SS side of unions outside pump oven, and connect copper jumpers.
4. Connect pump vent line to valve 1 (valve 1 closed).
5. Pull vac in line to valve 1, introduce argon 2 psi above atm.
6. Open valve 1.
7. Remove cap A, blow argon out cap A and also through surge tank line, connect surge tank line to cap A.
8. Close valve 1, remove pump vent line from valve 1, and replace cap. Close surge tank manifold valve to leave 2 psi in shipping container.
9. Connect pump vent line to valve 2.
10. Evacuate, fill with argon to 2 psi.
11. Open valve 2.
12. Remove cap B.
13. Blow argon through jumper to supply tank, connect to fill connection B.
14. Open valve C, blow argon from valve 2 and supply tank.
15. Close valve 2.
16. Remove pump vent line from valve 2, connect to valve C while blowing argon from line and valve.

17. Equalize pressures through system at 2 psi and close all valves.
18. Heat pump oven assembly to melt potassium.
19. Pull vacuum on supply tank.
20. Close top supply tank valve.
21. Close manifold valves, set pressure at 10 - 15 psig.
22. Open supply tank valve to pressurize free surface of shipping container.
23. Open supply tank fill valve gently. Supply tank will now fill.
24. Close fill valve.
25. Return supply tank to atmospheric pressure through valve 1.
26. Pressure jumper line through valve C to clear line.
27. Close all valves, freeze potassium.
28. Reverse procedure to get caps back on potassium shipping container.
29. Remove shipping container from system.
30. Wash out fill valve stub, dry, and cap off.
31. Reassemble system manifold lines.
32. Weigh shipping container. The supply tank holds 2 lbs., 1 oz., of 200° F potassium.

Check List for Potassium System Draining

1. Connect waste tank liquid tube to system drain valve. Connect waste tank vent to outside exhaust duct. (Tank is installed in pump oven.)
2. Connect spare manifold line (c) to valve on tee below condenser.
3. Drop supply tank pressure to 2 psig and close all manifold valves.
4. Heat entire system, as if for start-up.
5. Close valve in pump inlet line below condenser tee.
6. Open valve on bottom of supply tank.

7. Raise manifold argon pressure to 20 psig and open valve C to pressure line to condenser tee.
8. Open valve into condenser tee. All potassium will be pushed from condenser, boiler, and preheater.
9. When argon bubbles through supply tank, close isolation valve at preheater inlet.
10. Open valve in pump inlet line below condenser tee. All potassium will be pushed from thermal flowmeter line.
11. When argon bubbles through supply tank, close valve below condenser tee.
12. Open system drain valve.
13. Pressurize top of supply tank at 3 psig to push potassium into waste tank.
14. When argon bubbles through waste tank, open preheater inlet valve, pump inlet valve and blow argon through.
15. Close isolation valves on waste tank, boiler-preheater-condenser assembly, and supply tank. Close all manifold valves.
16. Turn off power and freeze potassium.
17. System may be disconnected. Wear masks, aprons, and gloves. Small potassium plugs may be found in the coupling between the pump and thermal flowmeter, and in the coupling between the EM flowmeter and preheater isolation valve.

APPENDIX III: PURITY OF POTASSIUM FILL MATERIAL

The potassium used in these experiments was transferred directly to the system as received from MSA Research Corporation without further purification.

Figure A-2 contains a copy of the analysis of the material used in the boiling inception experiments. The rinse-fill material was from a different container, but was of comparable purity.

MSA RESEARCH CORPORATION
Evans City, Pennsylvania 16033

MSA RESEARCH CORPORATION ANALYTICAL REPORT

Type of Material Potassium Lot No. ST8-857-1-1-2
Grade of Material High Purity Container No. 126

<u>Element</u>	<u>ppm</u>	<u>Element</u>	<u>ppm</u>	<u>Element</u>	<u>ppm</u>
Fe	-5	Cr	-5	Sr	-1
B	-10	Si	25	Ba	-3
Co	-5	Ti	-5	Ca	8
Mn	1	Ni	-5	Li	-
Al	-2	Mo	-3	Na	15
Mg	2	V	-1	K	Balance
Sn	-5	Be	-1	Rb	-
Cu	-1	Ag	-1	Cs	-
Pb	-5	Zr	-10	O ₂	<10 ppm
				C	49 ppm

Remarks: The prefix - designates less than.

Metallic impurity levels reflect analysis of the
chloride form of the metal.

Reference: Emission Spec Analysis - NUMEC Plate No. 11652-11653
11722-11728
Oxygen Analysis - Notebook No. 1347 Page No. 21
Carbon Analysis - Notebook No. 1347 Page No. 20

Certified by: James Larkin Quality Assurance
Research and Engineering

Figure A-2.

APPENDIX IV:
AN ANALYSIS OF TEMPERATURE MEASUREMENT ERRORS

With direct electrical heating, the energy is deposited in both the wall and the liquid metal. Some discussion of the significant temperatures involved is presented below. In this program, only temperatures on the outer tube wall were measured, using thermocouples spotwelded directly to the tube.

Two significant references to heat transfer in systems which have a heat source in the fluid volume as well as a heat source at the wall are cited in References A-2 and A-3. Based on these references and some estimates of the extreme conditions to be encountered in the experiment, estimates of the departure of the fluid bulk temperature and inside wall temperature from the reading of an outside thermocouple are made below. Consider the case in which the maximum possible volume heat source attainable with the existing equipment is applied to a columbium tube containing potassium liquid for somewhat typical conditions:

W	volume heat source in potassium = 2.2×10^6 watts/ft ³
q/A	wall heat flux to fluid, 6800 watts/ft ²
r _o	tube radius = 0.253 in./2 = 0.0105 ft
k	potassium thermal conductivity = 22 (BTU)/(ft ² hr °F/ft)
Pr	Prandtl Number = 0.0034

These conditions are sufficient to preheat to the boiling point a mass flow of 268 pounds per hour, corresponding to a mass velocity of $G = 210$ lb/ft² sec.

This latter value is approximately an order of magnitude above the level used in the present experiments.

By interpolation from Figure 5 of reference A-2, the volume heat source raises the wall fluid temperature above the centerline fluid temperature (for a Reynolds number of 40,000), so that

$$\frac{t_{\text{wall}} - t_{\text{bulk}}}{\left(\frac{W r_o^2}{k}\right)} = 1.0 \times 10^{-2}$$

The denominator has the value

$$\left(\frac{W r_o^2}{k}\right) = 37.6^\circ\text{F}$$

so that

$$t_{\text{wall}} - t_{\text{bulk}} = 0.38^\circ\text{F}$$

This result may be superimposed upon the wall to mixed-mean temperature difference caused by the wall heat flux to calculate the total difference. The wall to mixed-mean temperature difference may be computed from Martinelli's analysis, which for the present conditions may be approximated by

$$\frac{h d}{k} = 7$$

which yields,

$$h = 7350 \frac{\text{BTU}}{\text{ft}^2 \text{ hr } ^\circ\text{F}}$$

and

$$t_{\text{wall}} - t_{\text{bulk}} = 3.16^\circ\text{F}$$

The thermocouples are on the outside of the wall, and there is a temperature drop across the wall associated with the heat flow through the wall. Since the power is generated within the wall, the temperature drop is not uniform. In addition, the wall distribution is affected by the external heat losses. However, it may be shown that the variation across the wall is small in any case. Consider the flow of heat in the wall with the outside surface perfectly insulated. The temperature drop across the wall may be taken from reference A-4, page 131, so that

$$\frac{2k_t \Delta t_{\text{wall}}}{W_{\text{wall}} \delta^2} = 1$$

where

$$k_t = \text{the columbium thermal conductivity,} = 36 \frac{\text{BTU}}{\text{ft hr } ^\circ\text{F}}$$

$$\begin{aligned} \delta &= \text{wall thickness} = 0.030 \text{ in} \\ &= 0.0025 \text{ ft} \end{aligned}$$

$$W_{\text{wall}} = 9.3 \times 10^6 \frac{\text{BTU}}{\text{ft}^3 \text{ hr}}$$

For these data one obtains,

$$\Delta t_{\text{wall}} = 0.81^{\circ}\text{F}$$

Notice that heat losses from the outside decrease the temperature difference across the wall.

On the basis of the above calculation, it can be seen that the maximum difference between outer wall and bulk fluid temperatures is 4°F in the liquid-filled region. A typical run, however, would probably have a power input much less than the maximum, and this temperature difference decreases proportionately. Two other observations should be made. The first observation is that all components of the temperature difference can be calculated accurately, so that corrections may be made if necessary. The second observation is that the thermocouples are accurate to within $\pm 2^{\circ}\text{F}$, and since the junctions are made directly on the tube wall no more accurate calibration can be performed. The temperature drop between the outside wall thermocouple and the bulk liquid temperature will usually be less than the uncertainty in the temperature measurement.

An accurate measure of the mixed-mean temperature at the boiler outlet is provided by an unheated, insulated leg between the boiler and the condenser. This leg is provided with four thermocouples.

The location of the onset of boiling in experiments with a directly-heated boiler may be determined very accurately by the change in slope of the voltage gradient when boiling begins. The electrical current carried by the liquid transfers to the tube wall and a sharp change in gradient occurs. With the many potential measurements (one at each thermocouple station), the onset of boiling can be determined within a fraction of an inch.

APPENDIX V:
LIST OF INSTRUMENTS

<u>Name</u>	<u>Manufacturer</u>	<u>Model Number</u>	<u>Range</u>	<u>Accuracy</u>
A. C. Vacuum Tube Voltmeter	Hewlett-Packard Company	400H	0-300V	$\pm 1\%$
D.C. Vacuum Tube Microvoltmeter	" " "	425A	0-1V	$\pm 3\%$
Current Transformer 200:1	Harder Company	---	1000 amps	$\pm 1\%$ (calibrated against standard shunt)
Current Transformer	Esterline-Angus	Model D	-800 amps	$\pm 3\%$
Bourdon Tube Pressure Gauges	All calibrated against standard $\pm 1\%$	---		± 1 to 2%
Various Ashcroft, Marshalltown, USG Gauges			30 in vac-0-100 psi 0-30, 0-300, etc.	
Differential Pressure Transducers	Dynasciences Corp. (formerly Pace Eng.) a Whittaker Subsidiary	P7D P7D	-5-0-5 psi -30-0-30 psi	$\pm 0.5\%$ "
Discharge Vacuum Gauge	Consolidated Vacuum Corp.	GPH-100A	10^{-7} to 10^{-3} torr	Calibrated by Curtiss Assoc. $\pm 20\%$
Dual Range McLeod Gage	Stokes Vacuum Company		0.01 micron to 5000 microns	
Thermocouple Vacuum Gage	CVC	Type GTC-100	10^{-3} to torr	$\pm 20\%$
Thermocouples Chromel Alumel	Leeds & Northrup Company	---	0-2200°F	$\pm 1/2\%$
Potentiometer (all others calibrated against this potentiometer)	Leeds & Northrup Company	7553-G Type K-3	0-1.5V	$\pm 0.007\%$ or $0.5 \mu v$
Potentiometer	Leeds & Northrup Company	Type 8662	80 mv	$\pm 0.01\%$ or $2 \mu v$
24 Point Recorder/Speedomax G	Leeds & Northrup Company	---	0-2400°F	1%

LIST OF INSTRUMENTS (continued)

<u>Name</u>	<u>Manufacturer</u>	<u>Model Number</u>	<u>Range</u>	<u>Accuracy</u>
Single Point Recorder	Leeds & Northrup Company	---	0-800° F	1%
Single Point Recorder with Limit Switch	Brown-Honeywell	---	0-2400° F	1%
Water Flowmeter (for condenser)	Brooks Rotameter	8L-600	0-5 gpm	3%
Amplifier, Dual Channel	Brush	RD 5621 00	\pm 400V	1%
Oscillograph	Brush	Type BL-262		
Preamplifier	Sanborn	150-1500	100mv	\pm 1%
Dual Channel Recorder	Sanborn	152-100B	---	\pm 2%

APPENDIX REFERENCES

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